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# **Dark Matter and Astrophysics: What are we doing underground?**

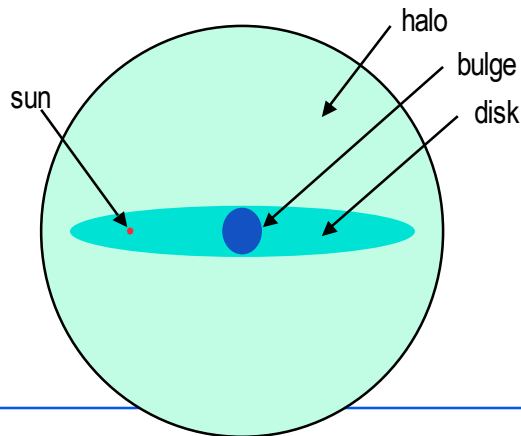
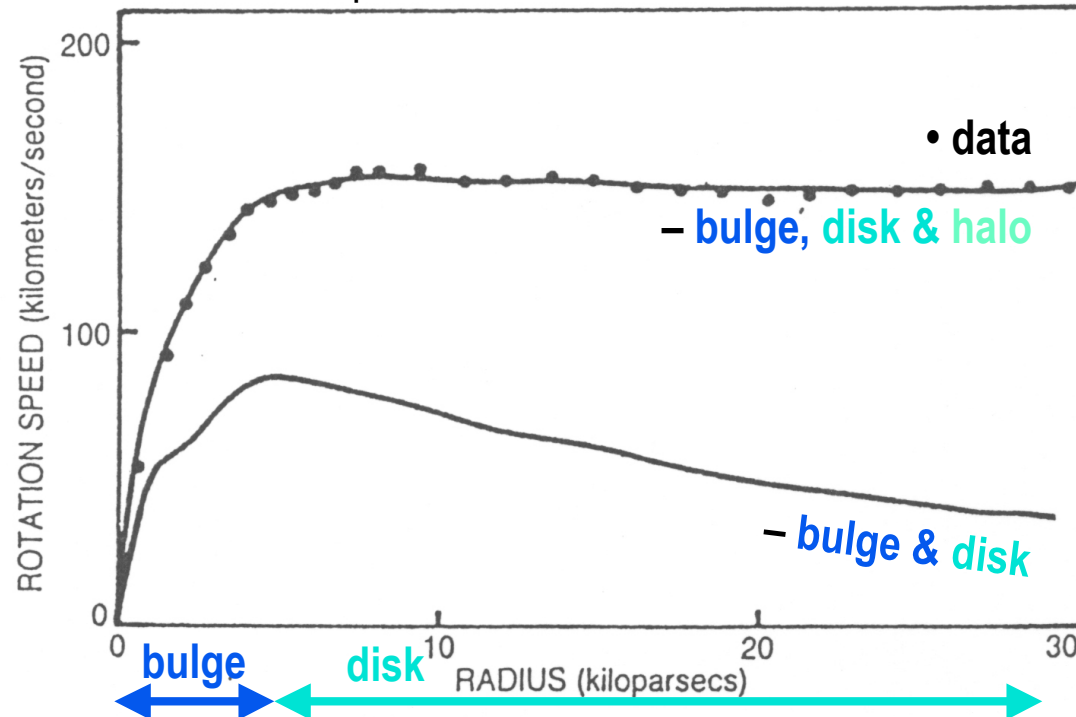
**Dan Akerib  
Case Western Reserve University  
and  
The CDMS Collaboration**

**Dusel S1 Science Meeting  
Berkeley, CA Aug 2004**

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# Dark Matter: the Missing Mass Problem

Galaxies – 10-100 kpc



Speed of orbits

→ Strength of Gravity

→ Missing Mass

$$F_{\text{centripetal}} = F_{\text{gravity}}$$

$$\frac{mV_r^2}{r} = \frac{GmM_{\text{total}}(r)}{r^2}$$

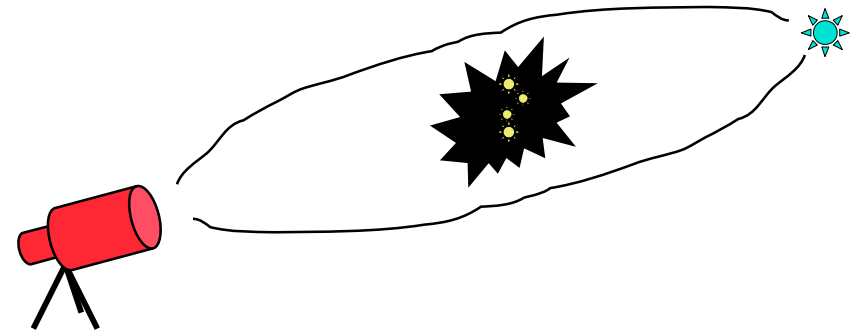
$$\rightarrow V_r = \sqrt{\frac{GM_{\text{total}}(r)}{r}}$$

$$\rho_{\text{dark}} \geq 10\rho_{\text{stars}}$$

## Other ways to 'see' it – gravitational lens



**Gravitational Lens**  
**Galaxy Cluster 0024+1654**  
Hubble Space Telescope · WFPC2

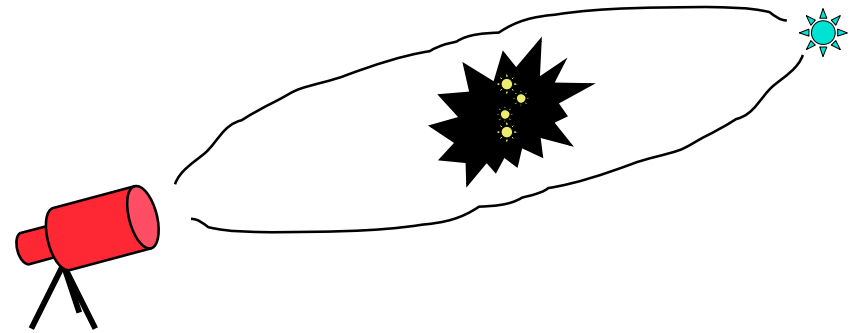


**Mass warps space,  
Lensing indicates  
strength of gravity  
→ dark matter!**

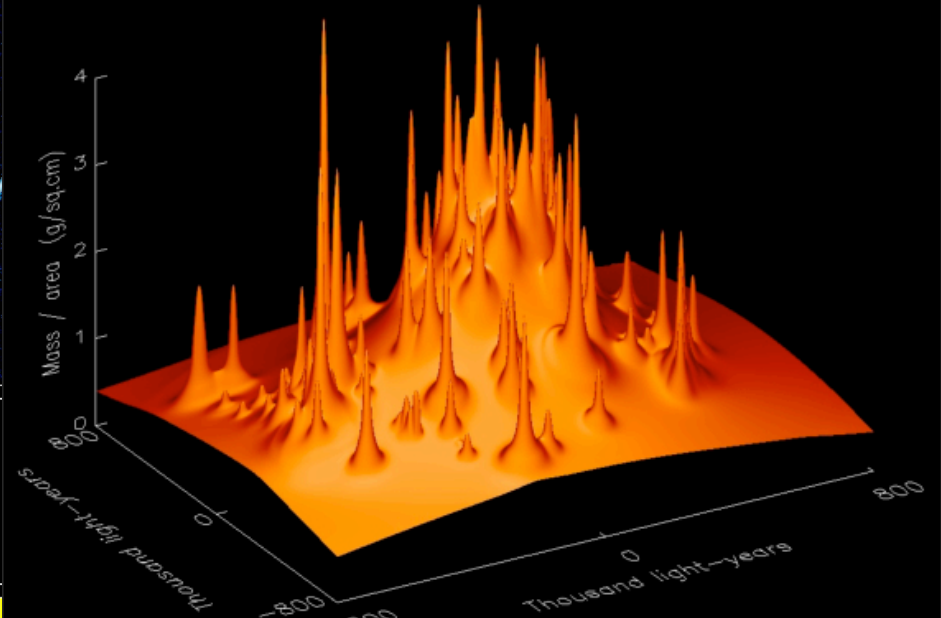
# Other ways to 'see' it – gravitational lens



**Gravitational Lens**  
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Hubble Space Telescope • WFPC2



**Quantitative fit to mass distribution**



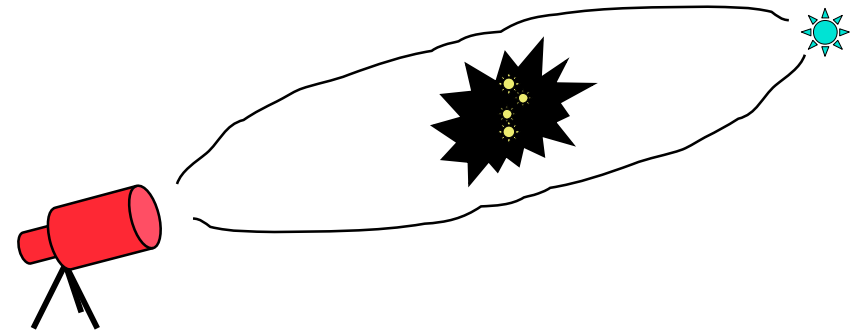
**Kochanski, Dell'Antonio, Tyson**

# Corroborating Evidence



**Gravitational Lens**  
**Galaxy Cluster 0024+1654**  
Hubble Space Telescope · WFPC2

Clusters – 1-10 Mpc



**Independent methods:**

**Lensing**

**Virial thm:  $\langle T \rangle = -\frac{1}{2} \langle U \rangle_{\text{dyn}}$**

**x-rays from bound gas**

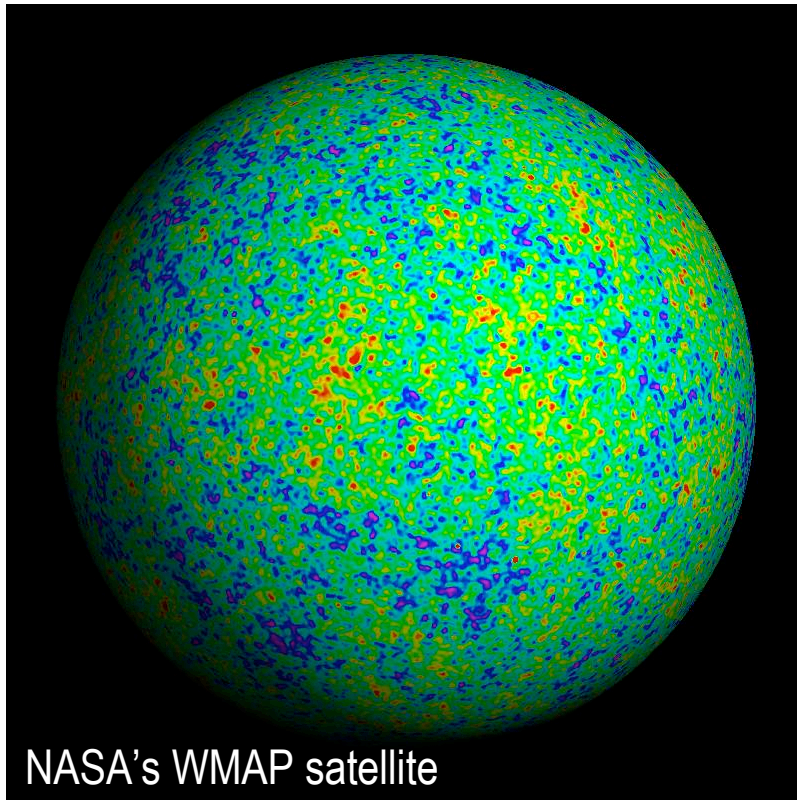
**$\rightarrow \Omega_{\text{dark}} = \rho / \rho_{\text{crit}} = 0.3$**

**$\rightarrow$  dark matter dominates**

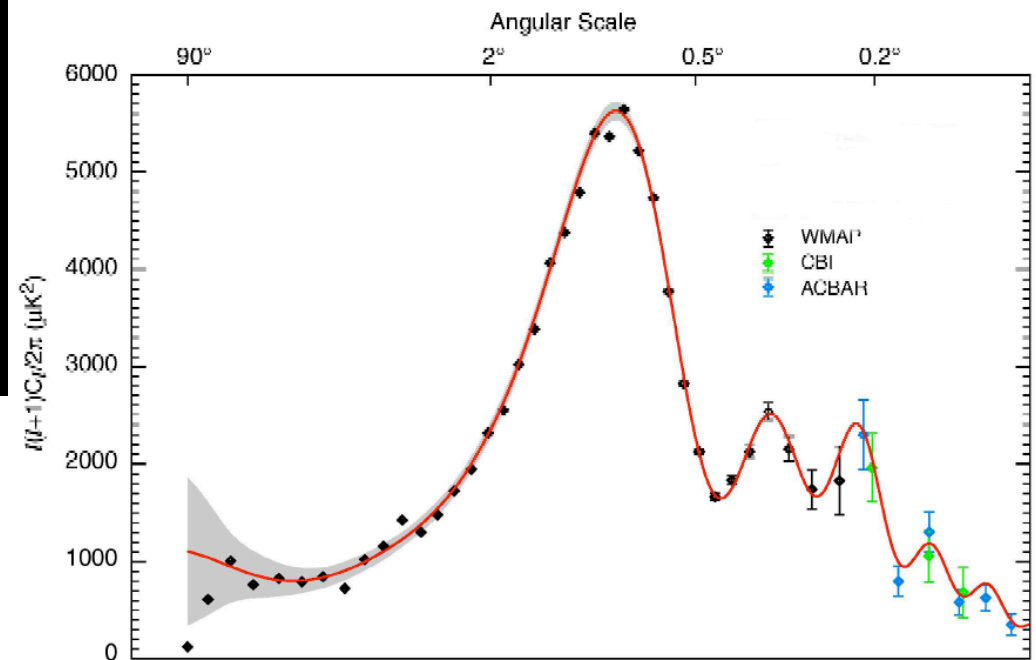
**$\rho_{\text{dark}} > 30 \rho_{\text{lum}}$**

# Cosmological scales

Tegmark, de Oliveira-Costa & Hamilton, astro-ph/0302496

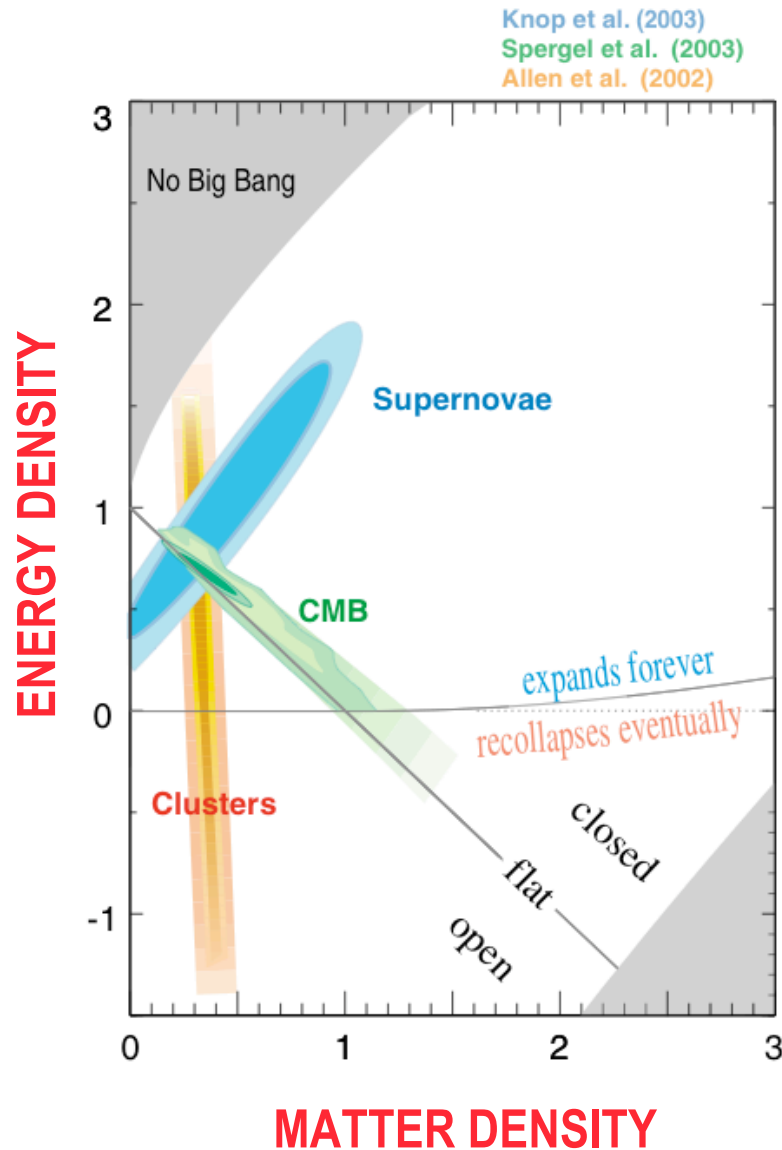


- CMB: 'power spectrum' – multipole expansion of anisotropy maps – 'standard yardstick' sensitive to overall geometry: **ENERGY plus MATTER**



Spergel et al. ApJS 148 (2003) 175

# Cosmological scales



- CMB: 'power spectrum' – multipole expansion of anisotropy maps – 'standard yardstick' sensitive to overall geometry: **ENERGY plus MATTER**

- SN1a: 'standard candle' sensitive to net expansion history: **ENERGY minus MATTER**

- Solution:  $\Omega_M = 0.3$ ; consistent with cluster measurements

# “Non-Baryonic” Dark Matter

## •Big Bang Nucleosynthesis

- ◆ Constrain baryon density based on relative abundance of light elements from hot big bang
- ◆ Measurements of D/H in primordial gas clouds (Burles & Tytler)

$$\Omega_B = 0.05 \pm 0.005$$

## •Clusters, CMB, SN1a (Pre-WMAP)

$$\Omega_{\text{Matter}} = 0.35 \pm 0.05$$

## •Spectacular confirmation from WMAP

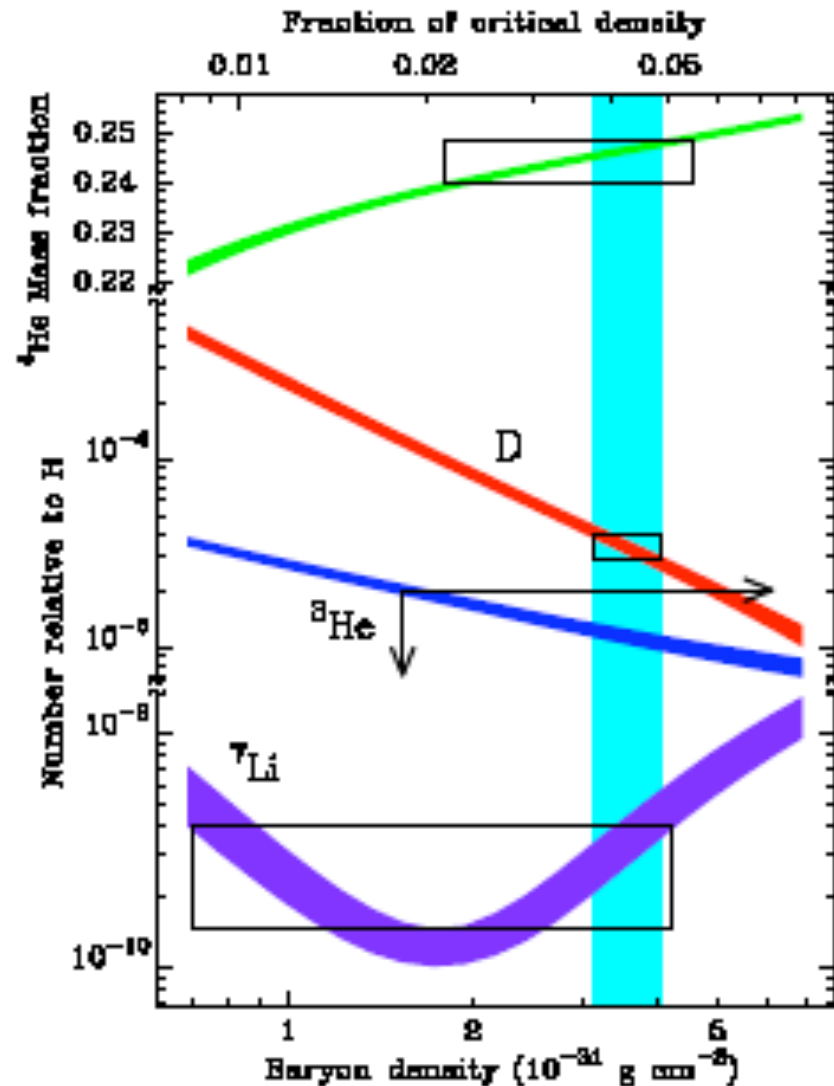
- ◆ ‘Standard Model’ confirmed

$$\Omega_B = 0.047 \pm 0.006$$

$$\Omega_{\text{Matter}} = 0.29 \pm 0.07$$

- ◆ + SDSS further constrain to

$$\Omega_{\text{Matter}} = 0.30 \pm 0.04$$



*D. Tytler et al /astro-ph/0001318*

# “Non-Baryonic” Dark Matter

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## •Nature of dark matter

- ◆ Non-baryonic
- ◆ Large scale structure predicts DM is ‘cold’ – non-relativistic at time of matter-radiation decoupling
- ◆ Required for “early” growth of gravitational instabilities
  - time for galaxy/large-scale structure formation

## •Particle physics – best candidates:

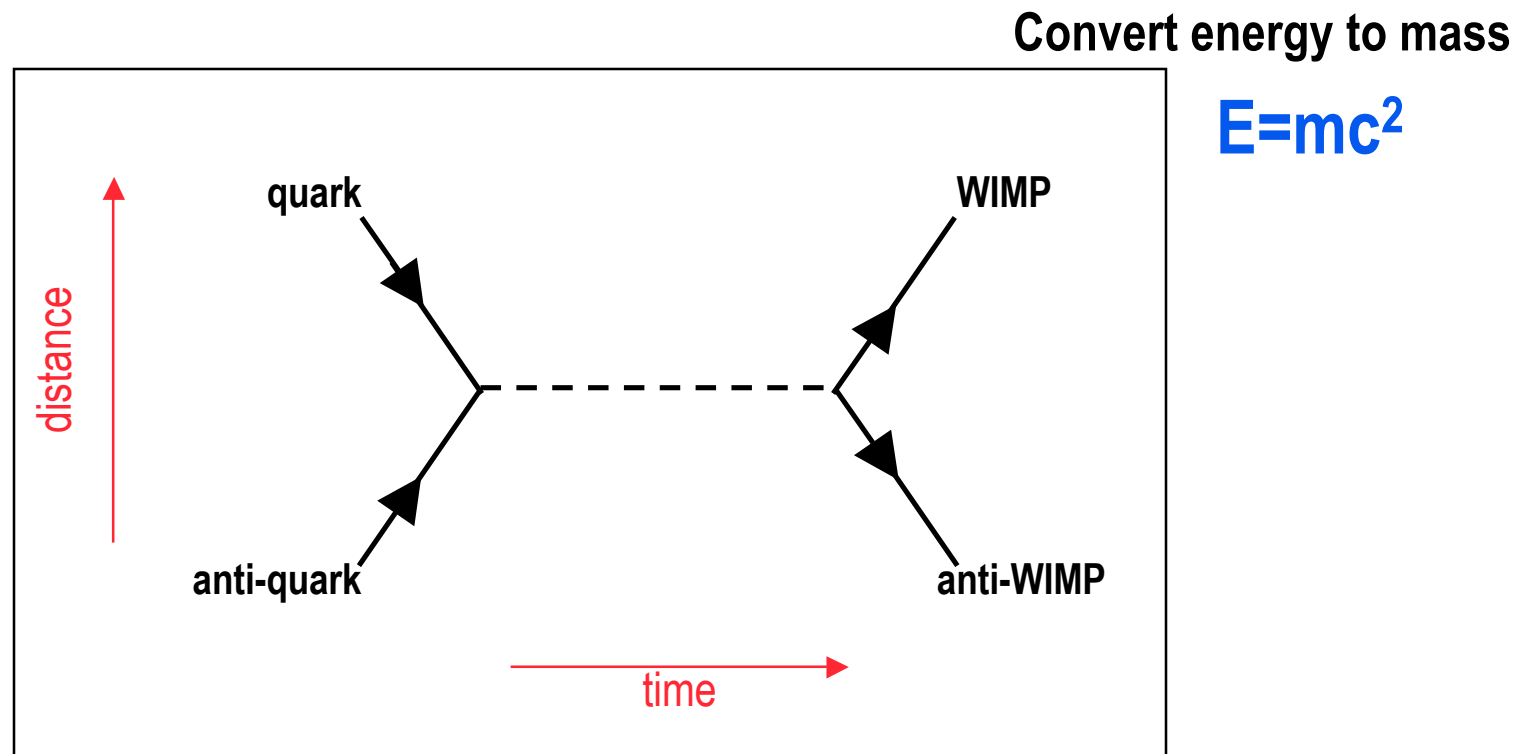
- ◆ WIMPs – Weakly Interacting Massive Particles
- ◆ Axions – solution to strong CP problem

# What is it? Extraordinary stuff!

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- Early Universe as Particle Factory

- ♦ Not enough protons and neutrons produced in the Big Bang



- A new type of particle: WIMPs = weakly interacting massive particles

Massive: source of gravity

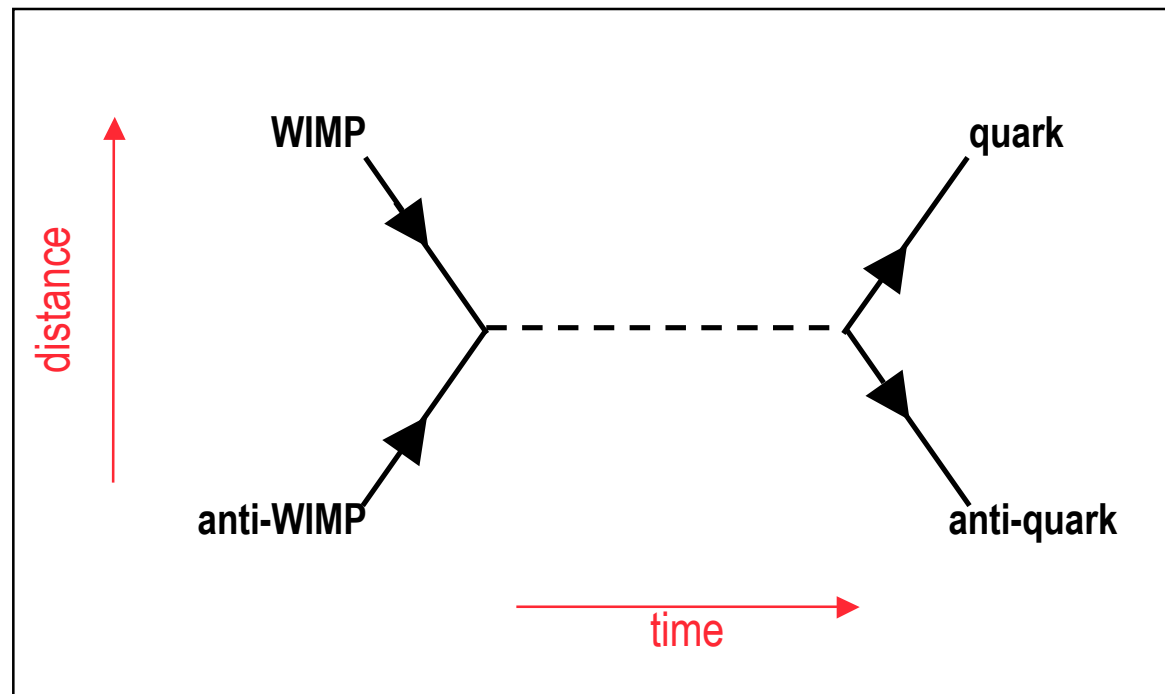
Weakly-interacting: not star forming

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# Still around?

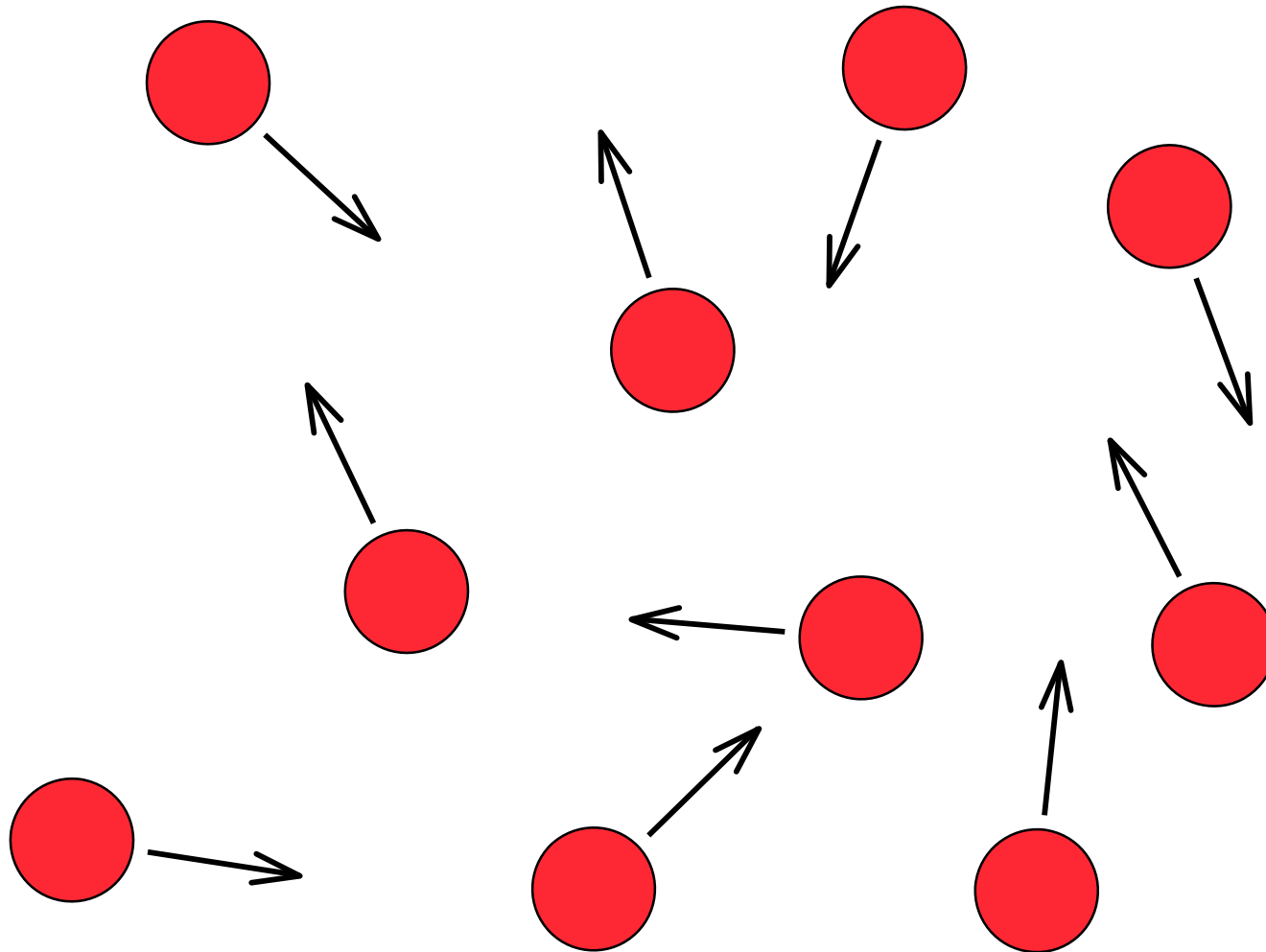
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## Expanding Universe and Weak Interactions



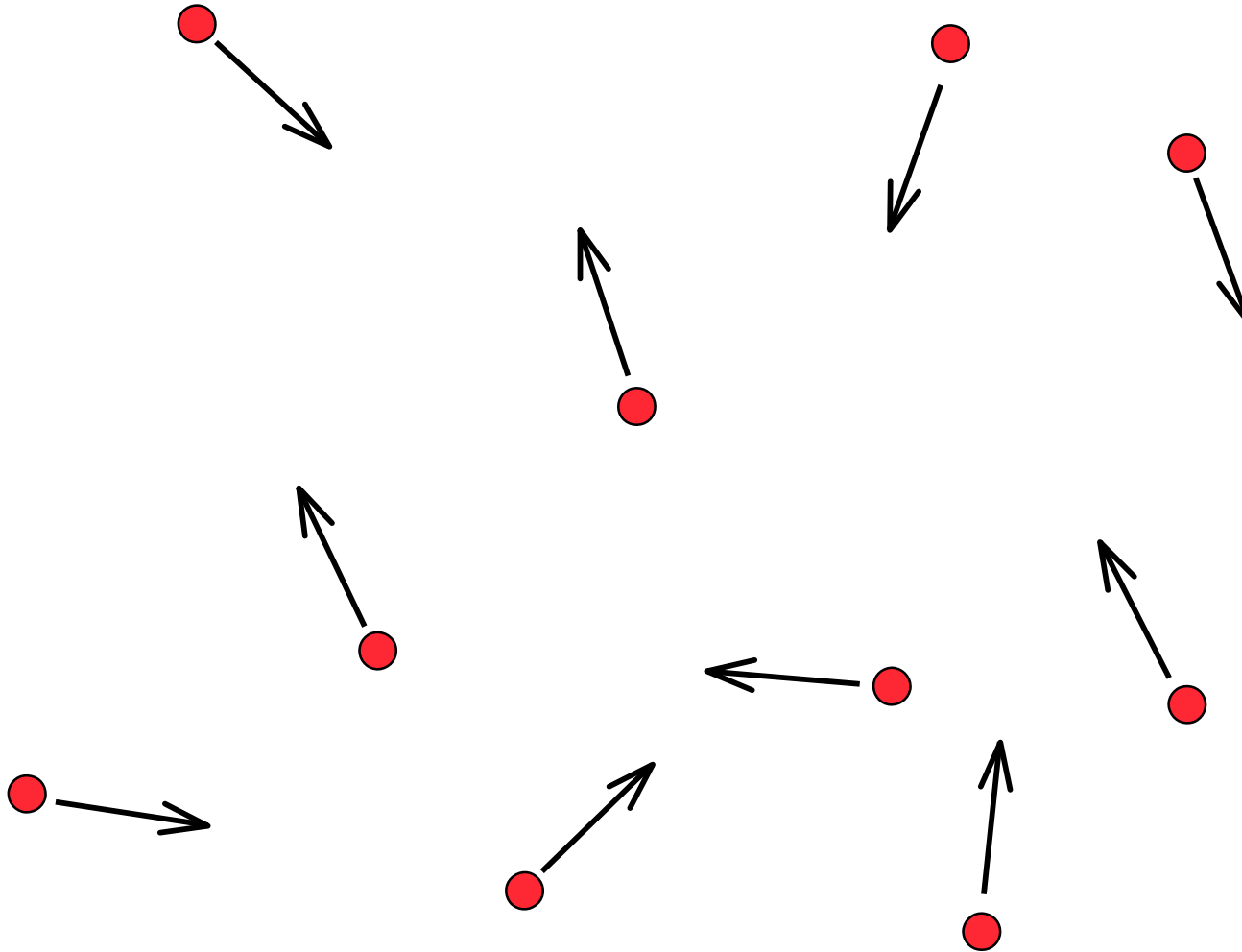
**Definition: cross section  $\rightarrow$  probability of collision**

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**Definition: cross section  $\rightarrow$  probability of collision**

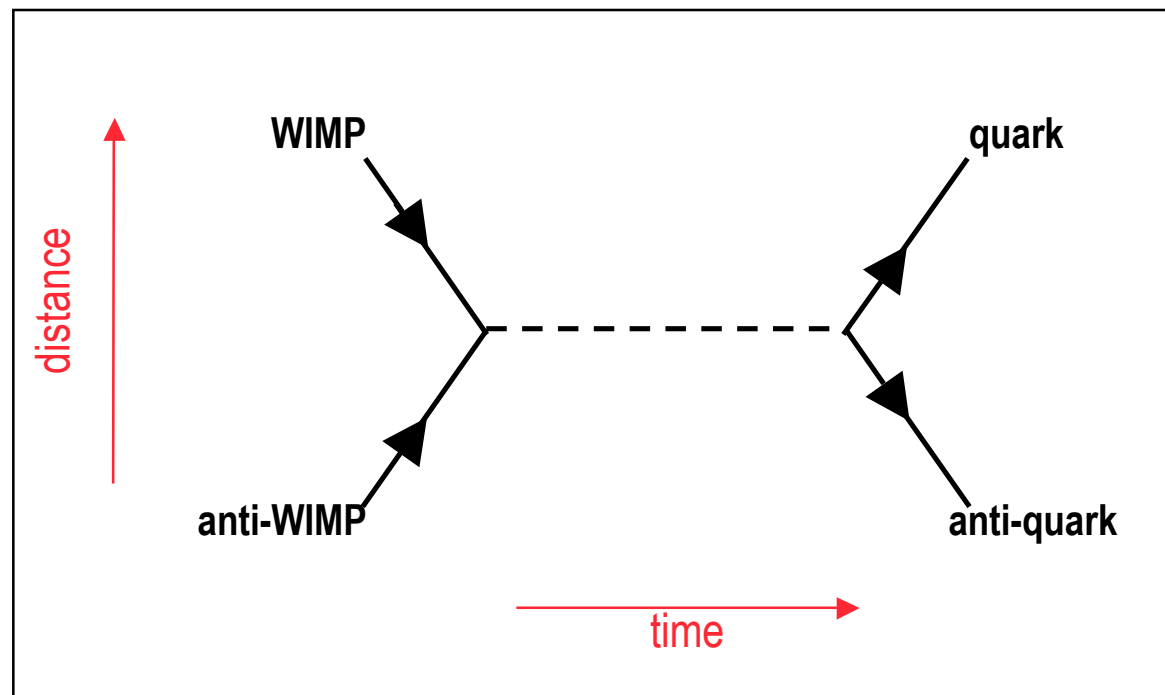
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# Still around?

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**Expanding Universe and Weak Interactions – annihilations stop if cross sections are small enough**



# Weakly Interacting Massive Particles

- WIMP pairs produced in dynamic equilibrium

- Annihilation **stops** when number density falls too low

$$H > \Gamma_A \sim n_c \langle \sigma_A v \rangle$$

- annihilation rate slower than Hubble expansion (“**freeze out**”)

- mean free time > age

- For  $\Omega_w \approx 0.3$

- ◆  $M \sim 10\text{-}1000 \text{ GeV}$

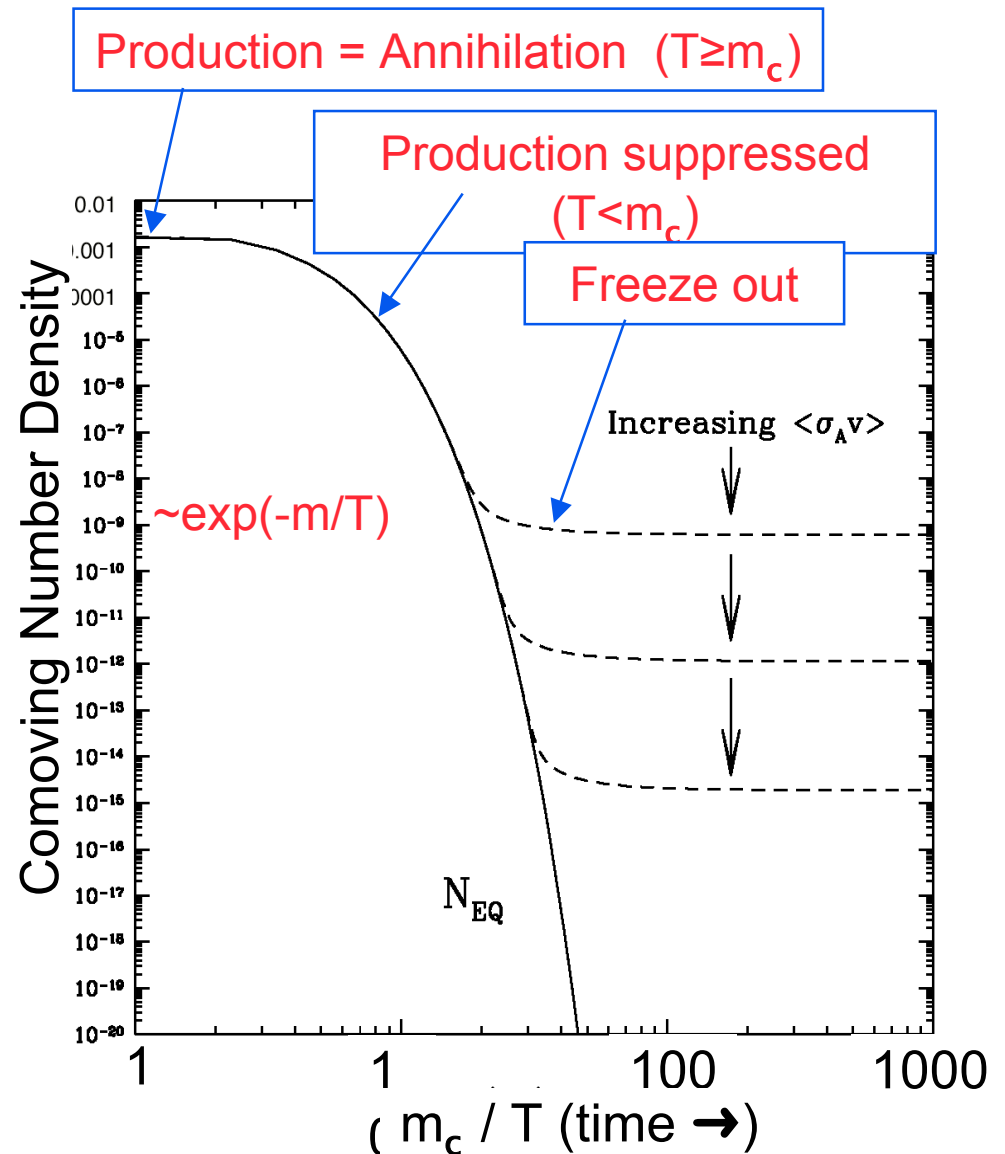
- ◆  $\sigma_A \sim \text{electroweak}$

SUSY/LSP

- $T_{FO} \sim m/20$

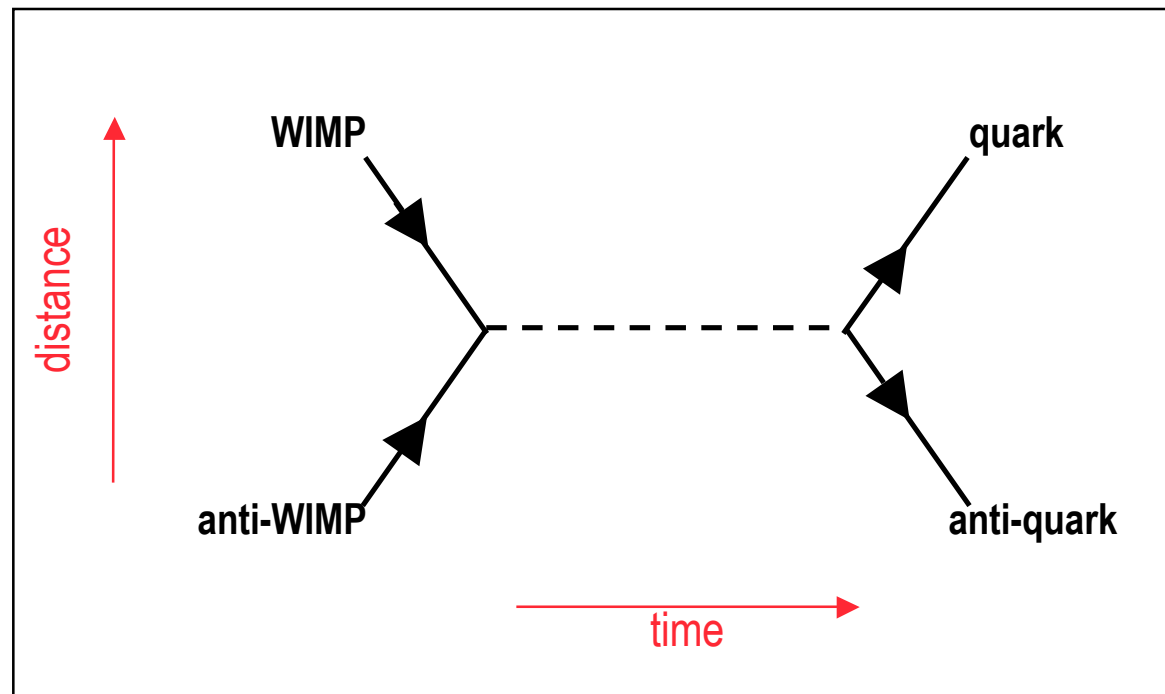
- ◆ Non-relativistic

‘Cold’

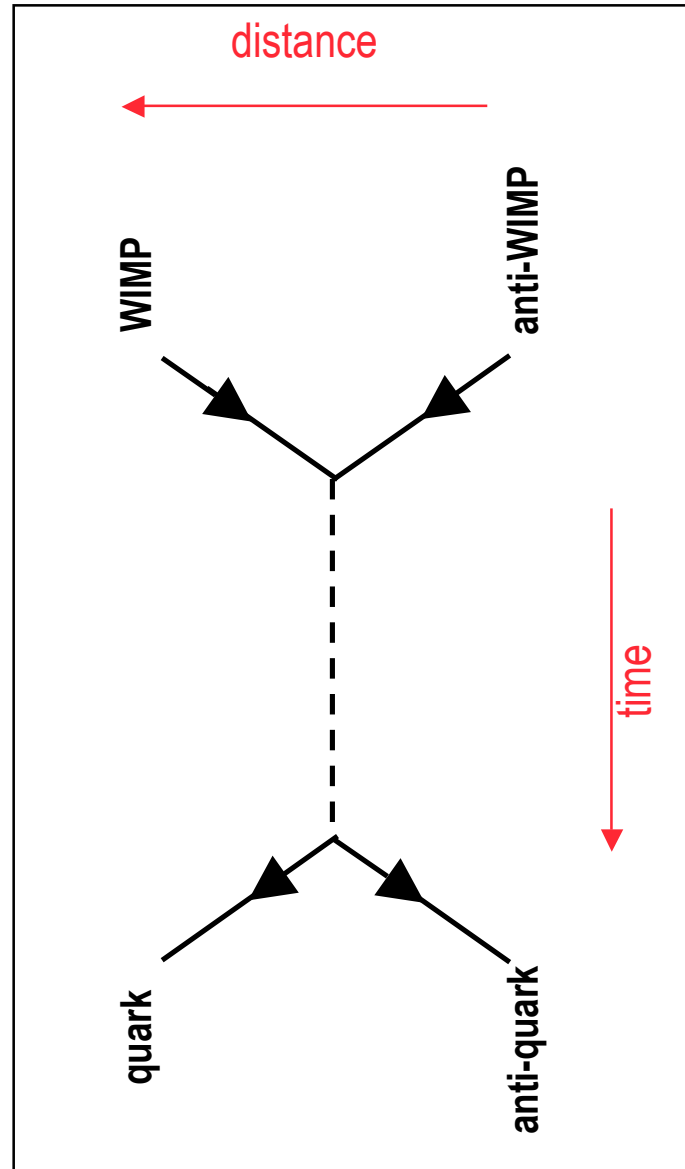


# Annihilation $\leftrightarrow$ Scattering

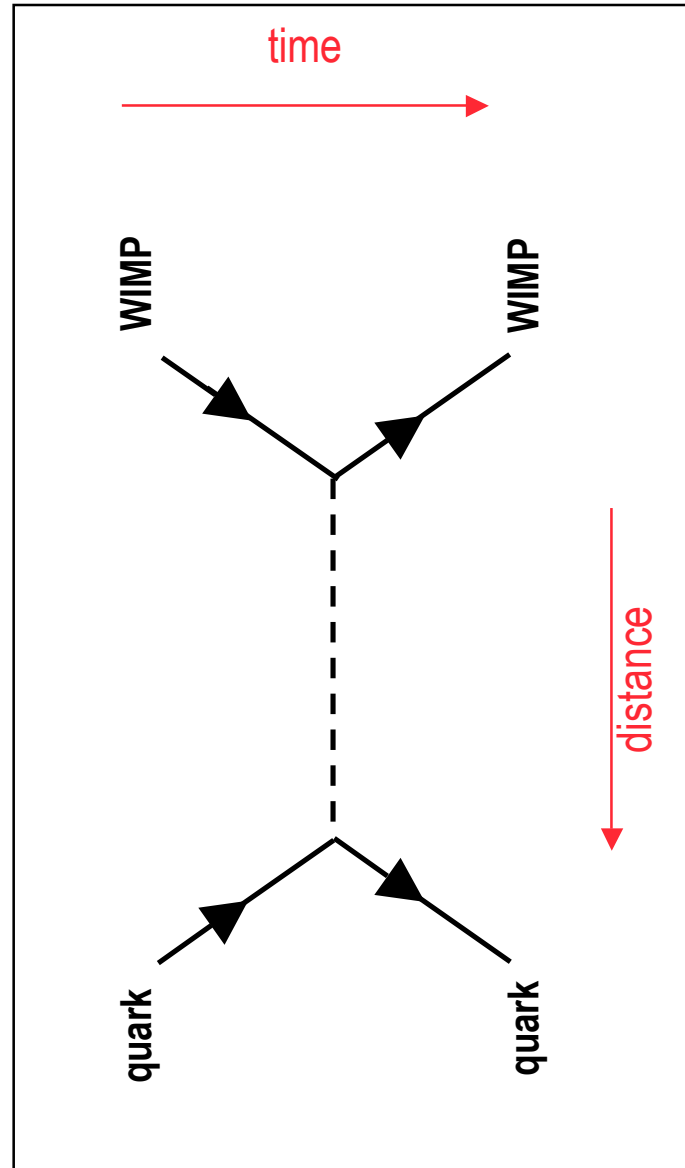
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# Annihilation $\leftrightarrow$ Scattering



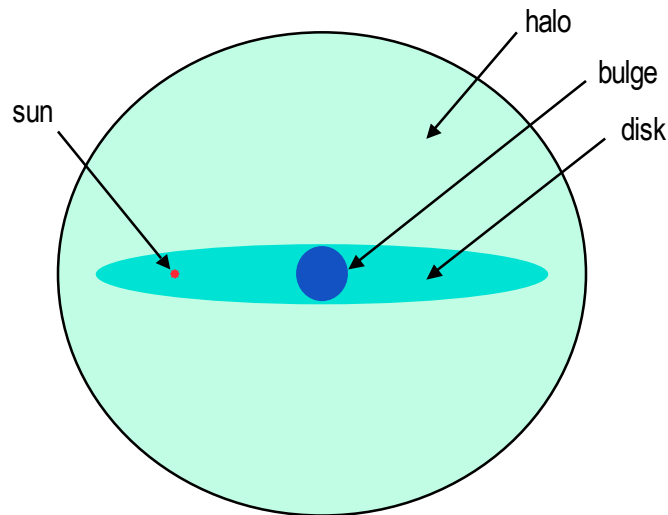
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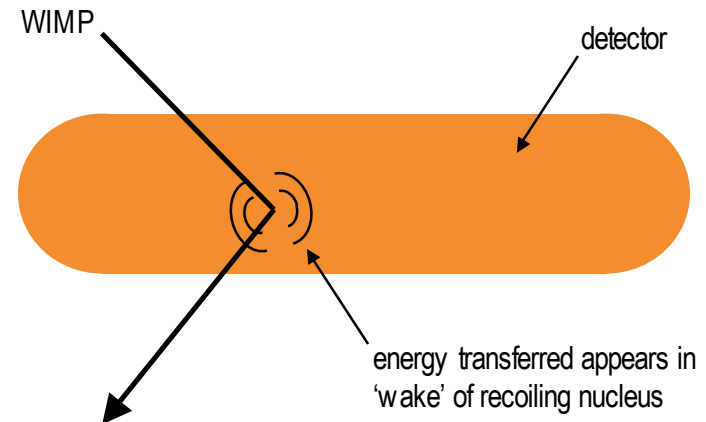
# WIMPs in the Galactic Halo

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## WIMPs – the source of Mass in the Rotation Curves?



The Milky Way



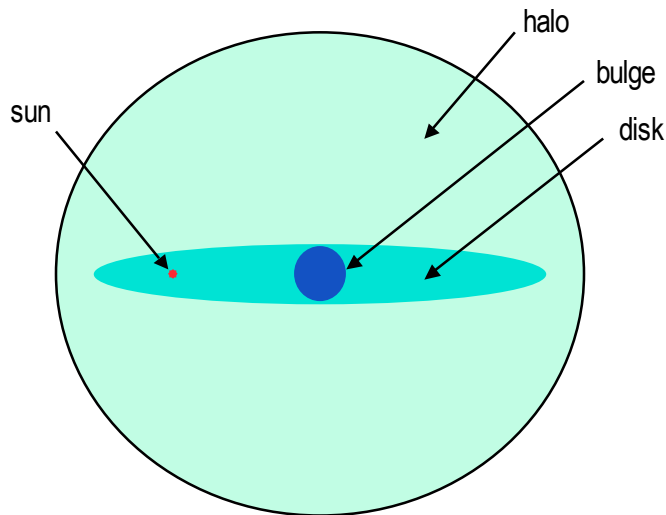
WIMP-Nucleus Scattering

## Scatter from a Nucleus in a Terrestrial Particle Detector

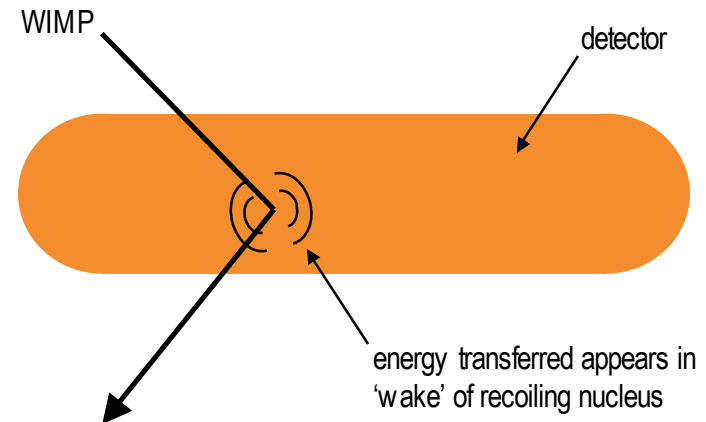
**Big Problem: weakly interacting. Expect less than one-a-day in a kilogram detector with  $E \sim 10\text{keV}$**

# WIMPs in the Galactic Halo

## WIMPs – the source of Mass in the Rotation Curves?

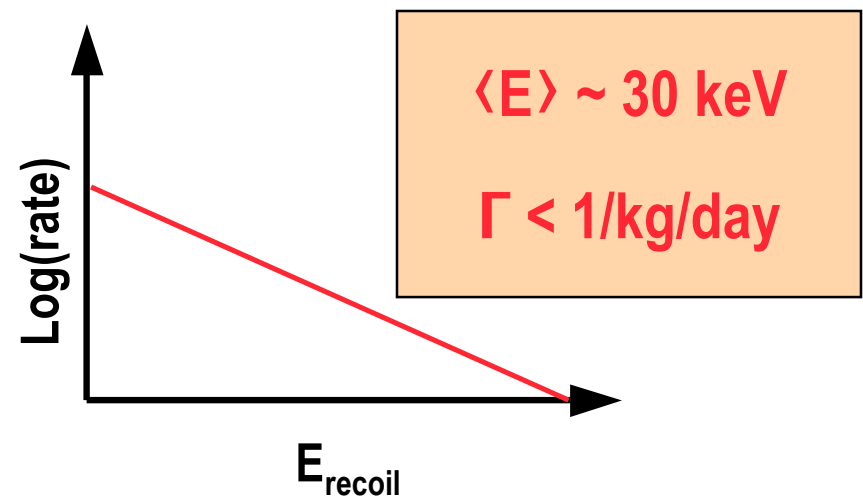


The Milky Way



WIMP-Nucleus Scattering

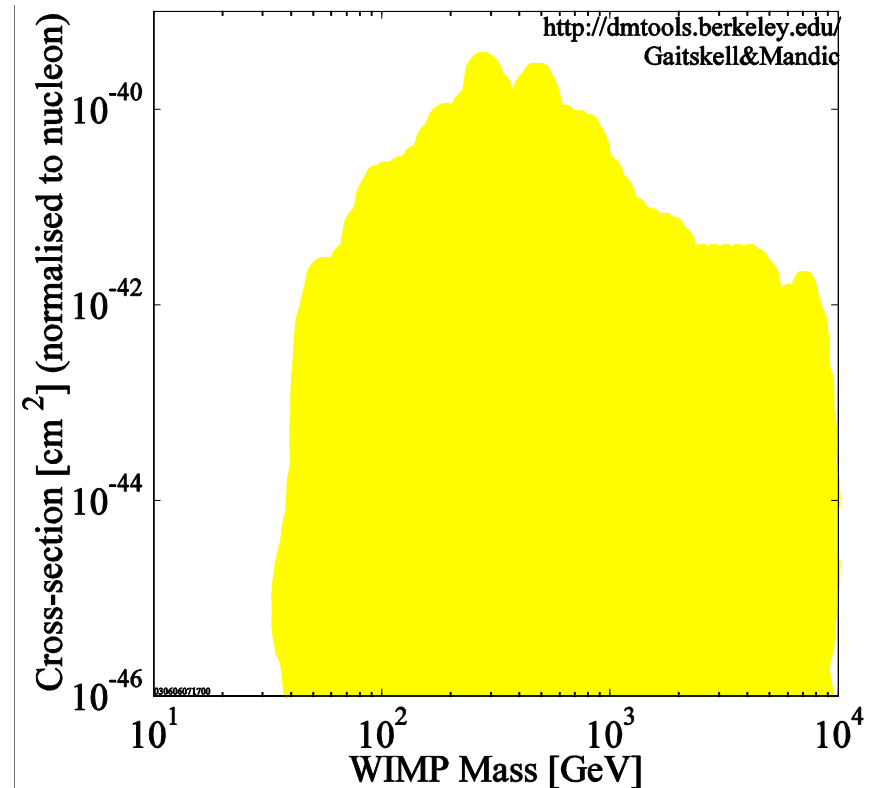
## Scatter from a Nucleus in a Terrestrial Particle Detector



# SUSY Dark Matter: elastic scattering cross section

- The 'standard' progress plot in our business
  - ◆ Sample SUSY parameter space
  - ◆ Apply accelerator and other particle physics constraints
  - ◆ Require relic density  $O(\text{critical})$
  - ◆ Local density is known
- Extract WIMP-nucleon cross-section ( $\sim$ event rate) versus WIMP mass

Least constrained

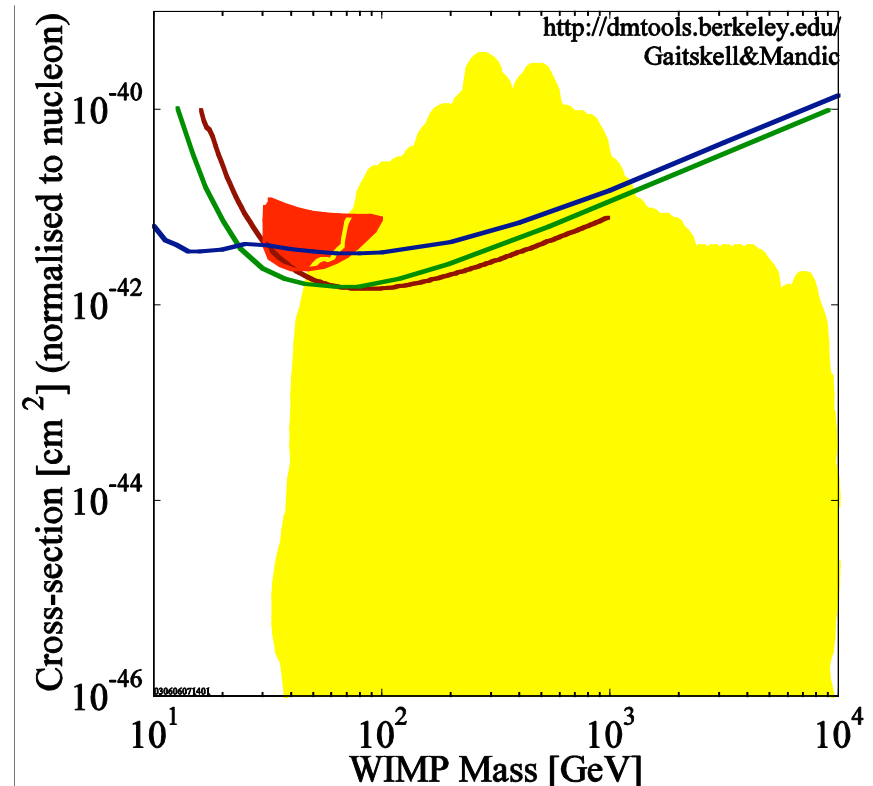


DATA listed top to bottom on plot  
Gondolo et al. SUSY (Mixed Models)  
03/06/06 07:17:00

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Experimental  
bounds

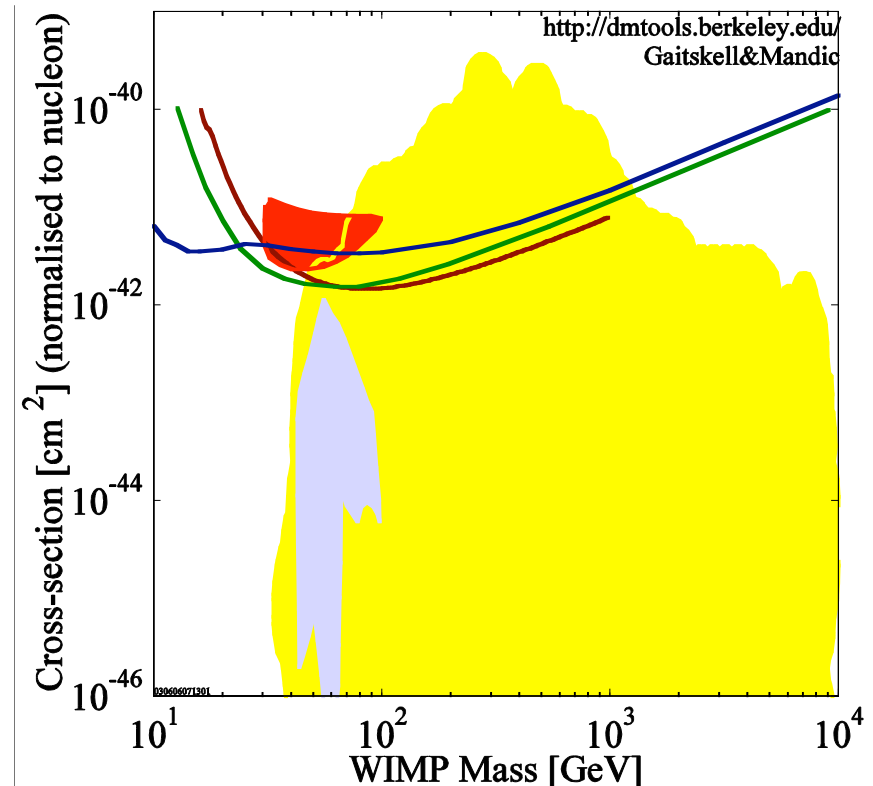


DATA listed top to bottom on plot  
CDMS June 2003, bkgd subtracted  
DAMA 2000 58k kg-days NaI Ann.Mod. 3sigma,w/o DAMA 1996 limit  
ZEPLIN 1 Preliminary 2002 result  
Edelweiss, 32 kg-days Ge 2000+2002+2003 limit  
Gondolo et al. SUSY (Mixed Models)  
030606071401

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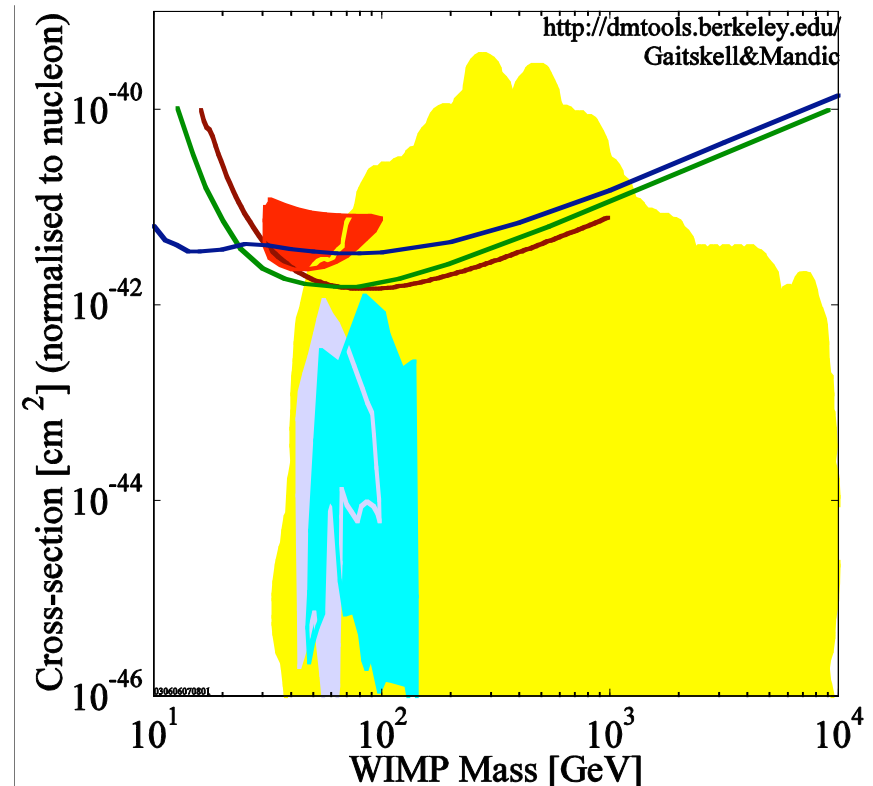
Constrain models



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Edelweiss, 32 kg-days Ge 2000+2002+2003 limit  
Corsetti & Nath, mSUGRA hep-ph/0003186  
Gondolo et al. SUSY (Mixed Models)  
030606071301

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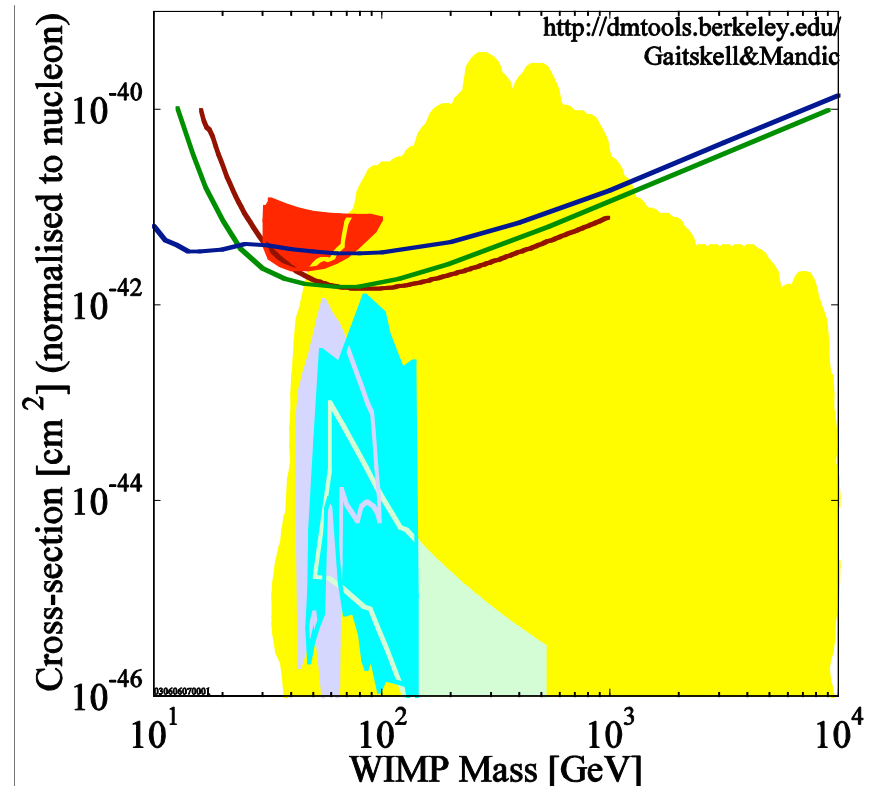
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Mandic,Pierce,Gondolo,Murayama mSUGRA( $M_3 < 1 \text{ TeV}$ )hep-ph0008022  
Corsetti & Nath, mSUGRA hep-ph0003186  
Gondolo et al. SUSY (Mixed Models)  
030606070801

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Constrain models

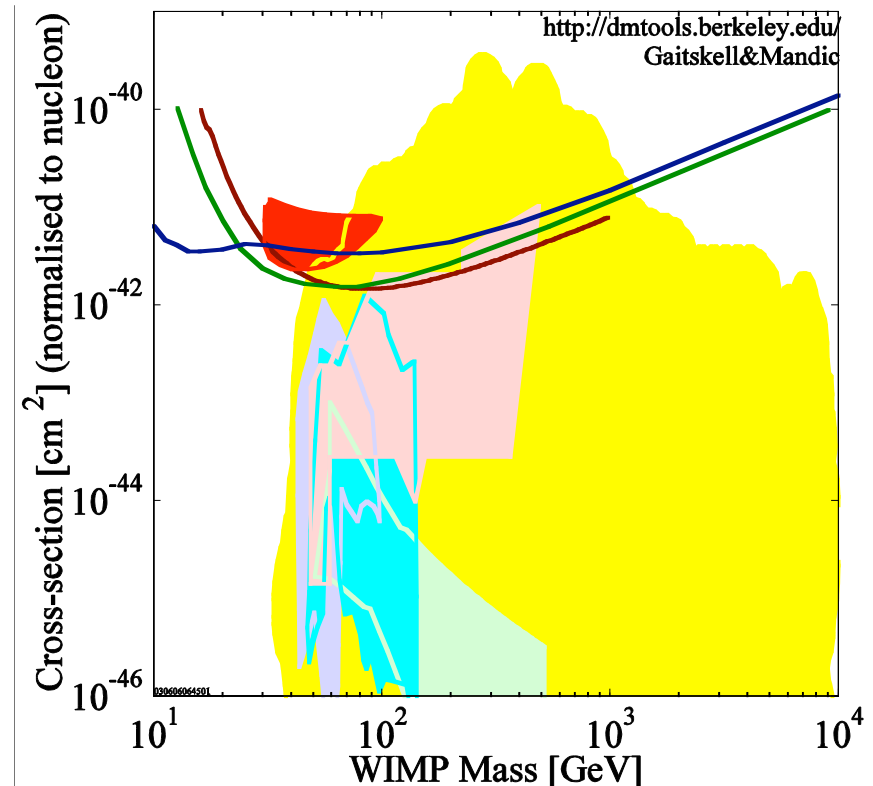


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Ellis et al., Spin indep. sigma in CMSSM  
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03/06/06 07:00:01

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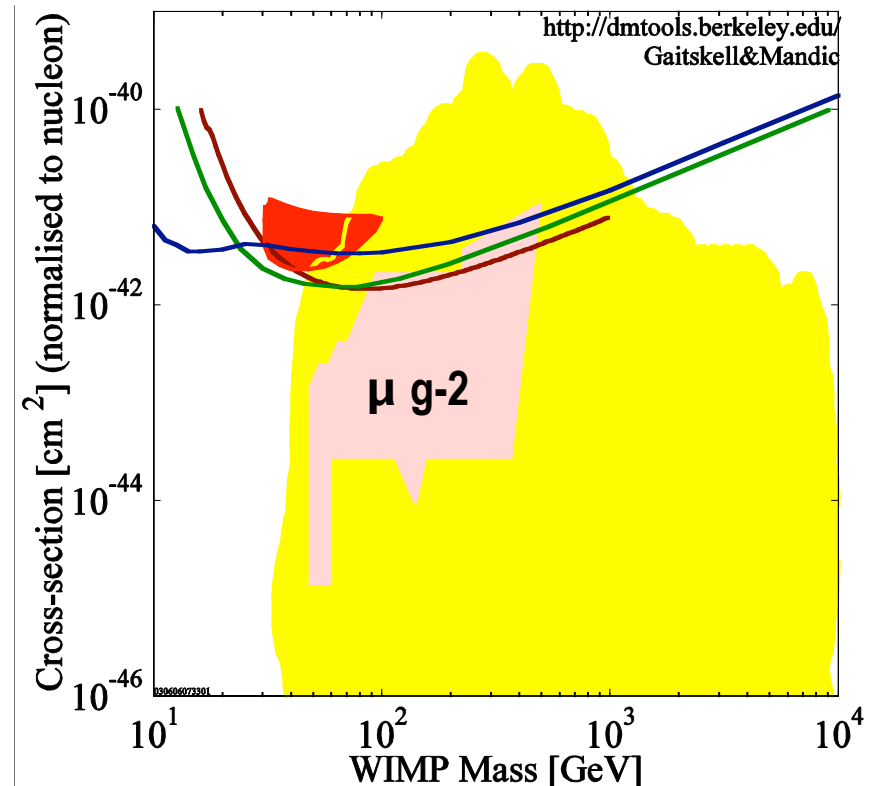


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03/06/06 07:01

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Finally a 'bottom'?



DATA listed top to bottom on plot  
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ZEPLIN 1 Preliminary 2002 result  
Edelweiss, 32 kg-days Ge 2000+2002+2003 limit  
Baltz and Gondolo, spin indep. sigma in MSSM, with muon g-2 constraint  
Gondolo et al. SUSY (Mixed Models)  
03/06/06 07:33:01

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**How do we make  
measurements?**

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# Particle detection

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Detected particle  
ionizes the gas,  
collect the charge...

Or detected particle  
produces a flash of  
light, which is  
converted to  
'photoelectrons'...

Or detected particle  
interacts with a  
nucleus, which  
ionizes the gas,  
which...

Or...

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# Background Radioactivity

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# It's in the air: a practical demonstration

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Before...



## It's in the air: a practical demonstration

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During...



## It's in the air: a practical demonstration

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After...



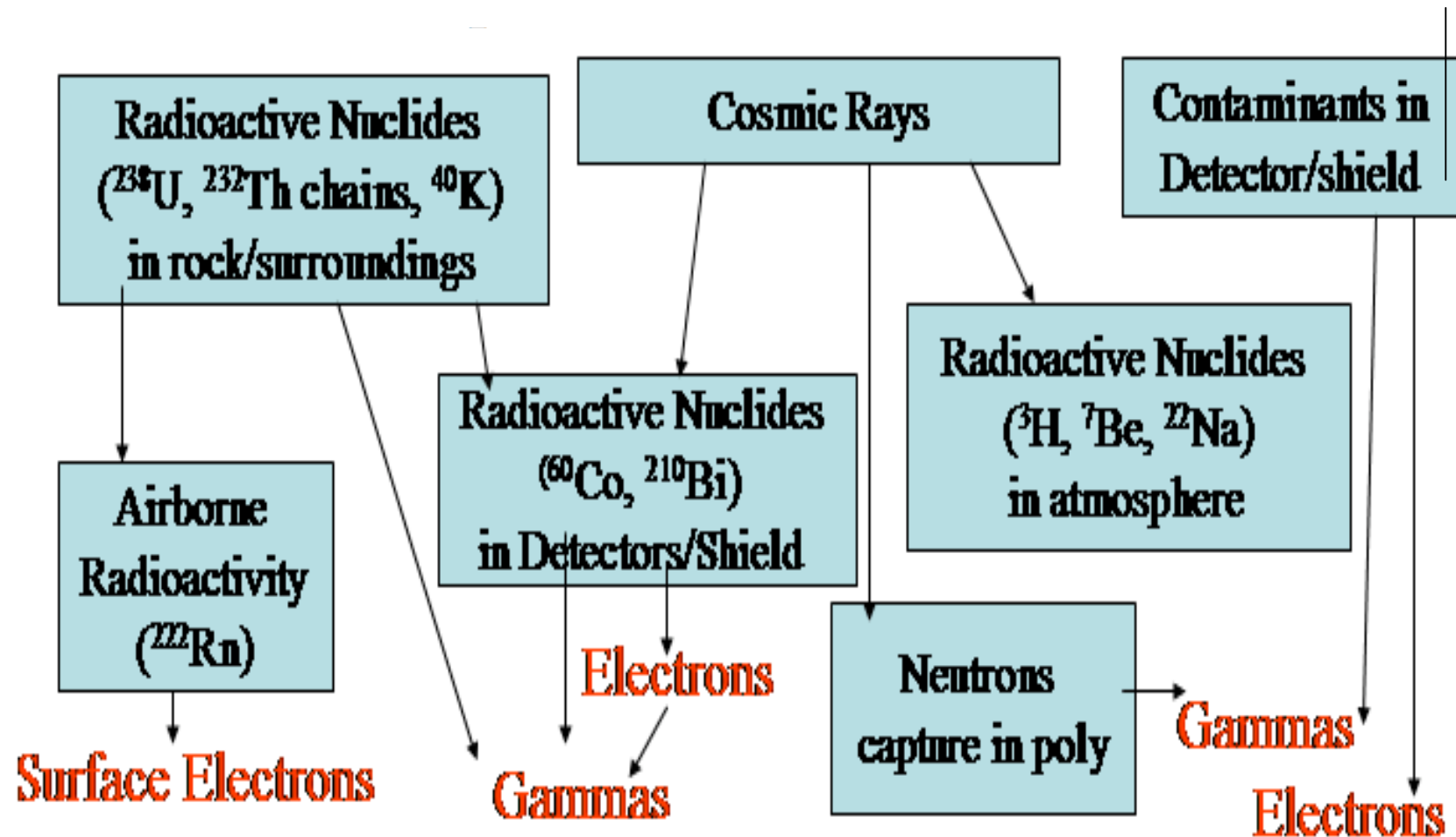
**What nature has to offer**

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**What you hope for!**

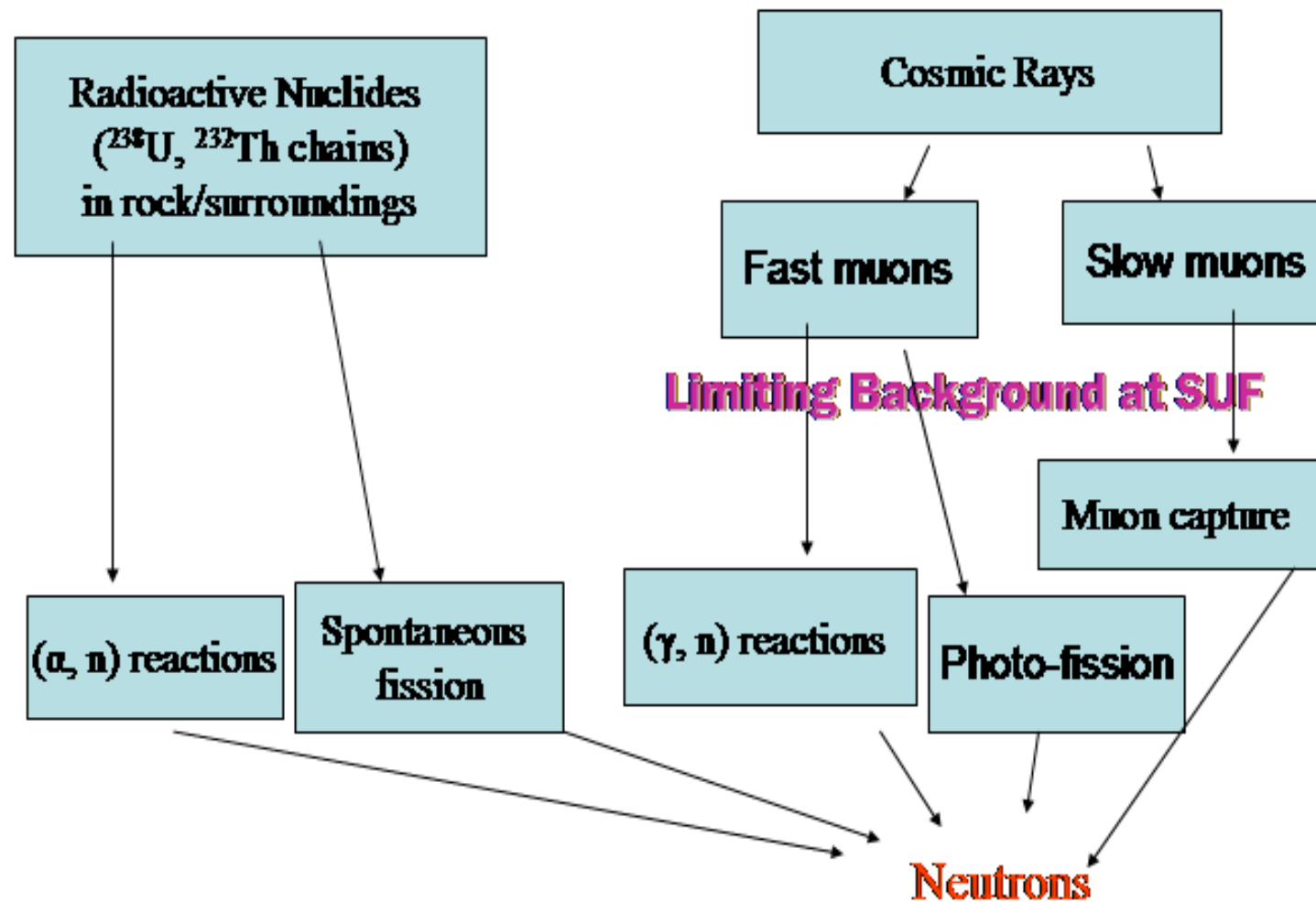


# Gamma and Electron Backgrounds

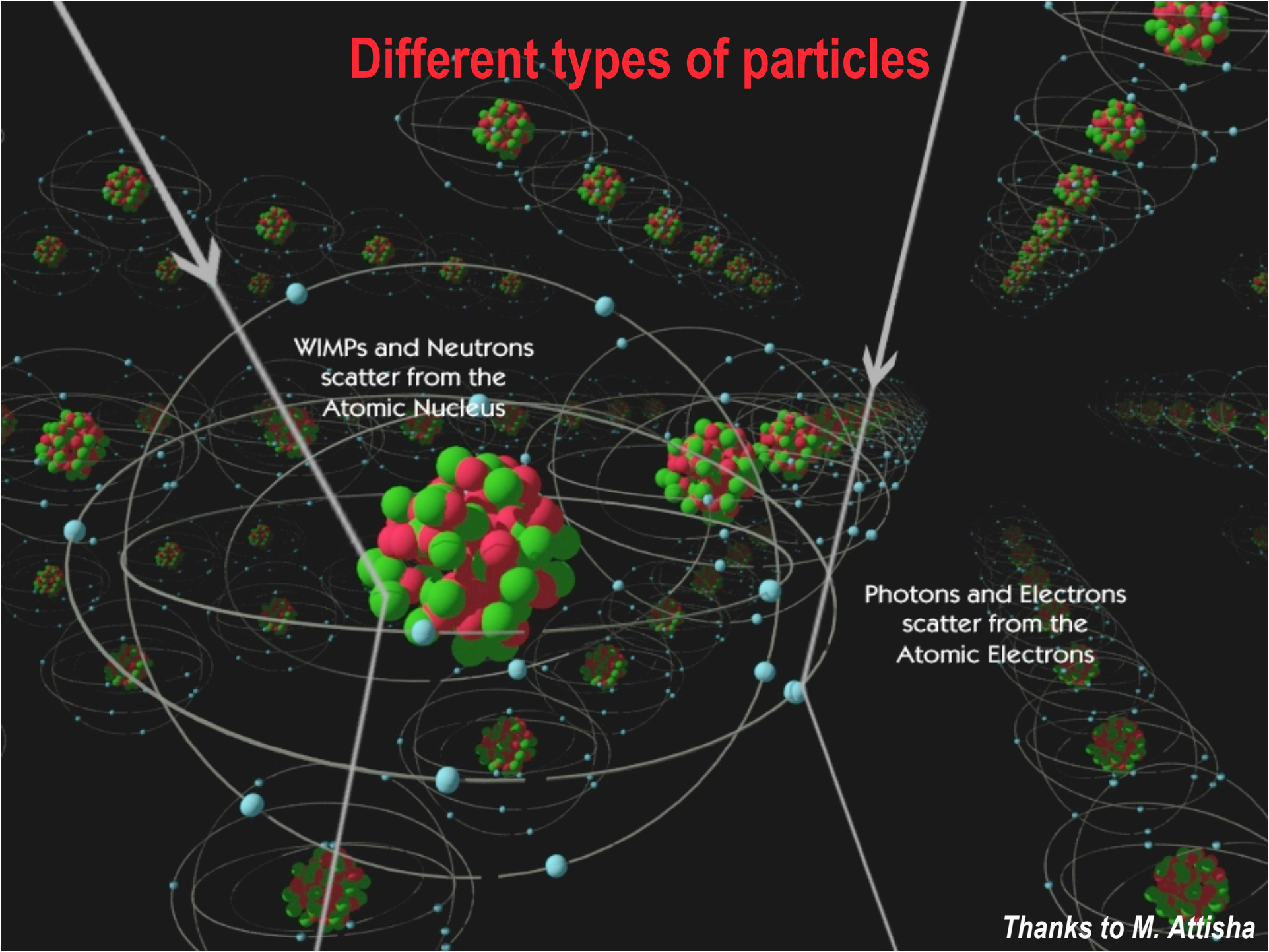


# Neutron Backgrounds

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# Different types of particles



The diagram illustrates the interaction of different particles with atoms. Atoms are represented by a central nucleus of red and green spheres, surrounded by concentric elliptical orbits with small blue spheres (electrons). Two white arrows originate from the top left and top right, pointing towards the center. The left arrow is labeled 'WIMPs and Neutrons scatter from the Atomic Nucleus' and points directly at a central nucleus. The right arrow is labeled 'Photons and Electrons scatter from the Atomic Electrons' and points towards the electron orbits of a nucleus on the right. The background is black.

WIMPs and Neutrons  
scatter from the  
Atomic Nucleus

Photons and Electrons  
scatter from the  
Atomic Electrons

*Thanks to M. Attisha*

# Overview of different techniques

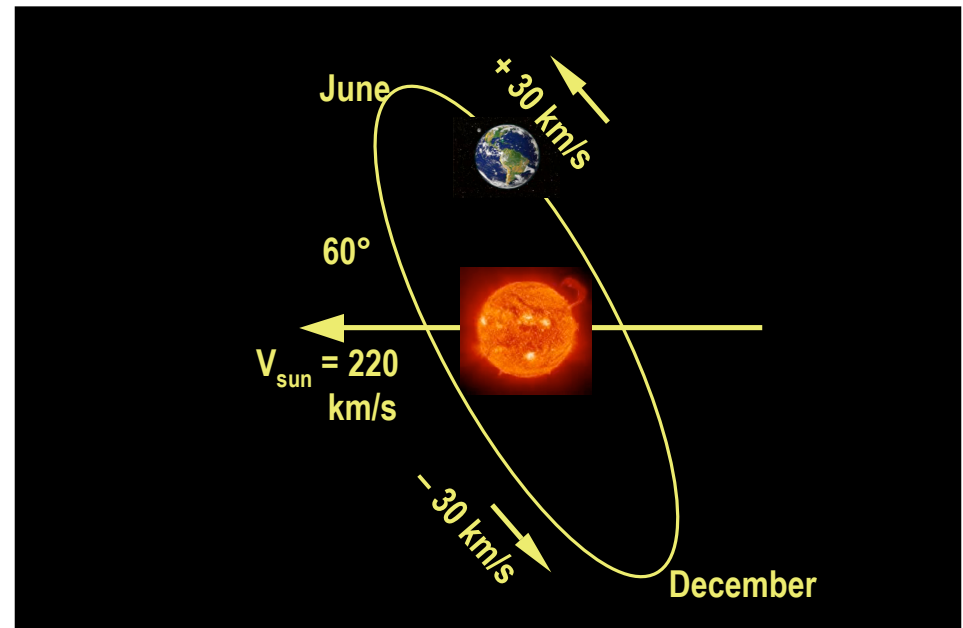
- Detector Technologies - different way of rejecting gammas/betas

- ◆ CDMS: phonons (~heat) and ionization
- ◆ Edelweiss: heat and ionization
- ◆ LXe: light and ionization
- ◆ Cresst: heat and light
- ◆ Drift: track topology in gas
- ◆ Superheated: immune

- The CDMS story, parts 1 and 2 illustrate the issues of background rejection and the neutron/depth question -- common to all WIMP dark matter searches

- Signatures

- ◆ Calorimetry
- ◆ Annual modulation
  - Variation of earth's motion through galactic halo
- ◆ Directional modulation
  - Earth's rotation



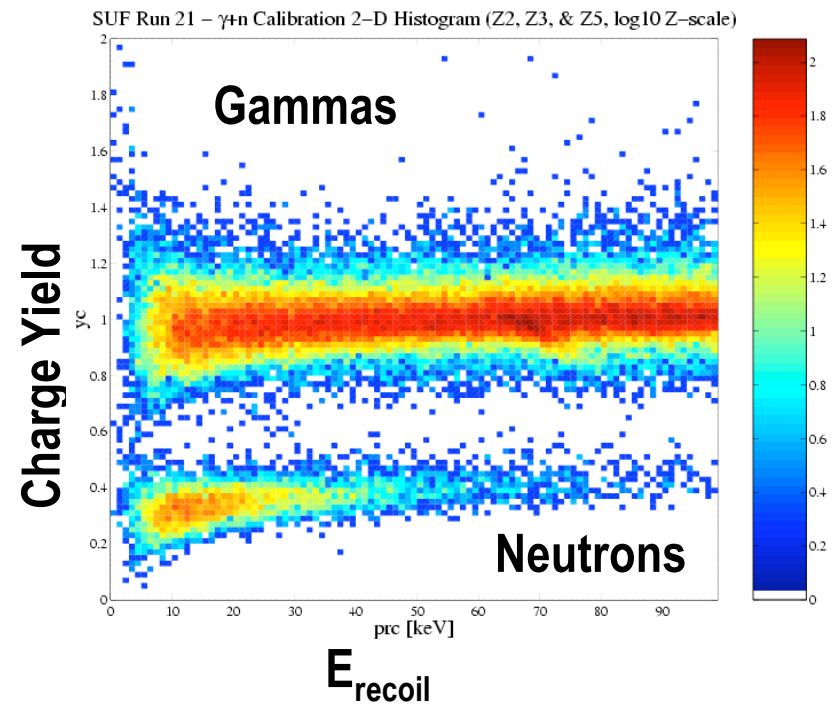
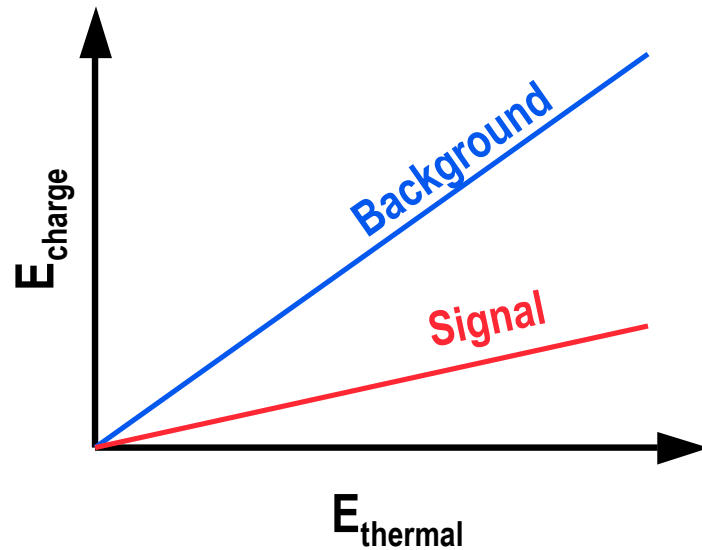
# Getting rid of the 'haystack': an example

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WIMPs 'look' different – recoil discrimination

Photons and electrons scatter from electrons

WIMPs (and neutrons) scatter from nuclei

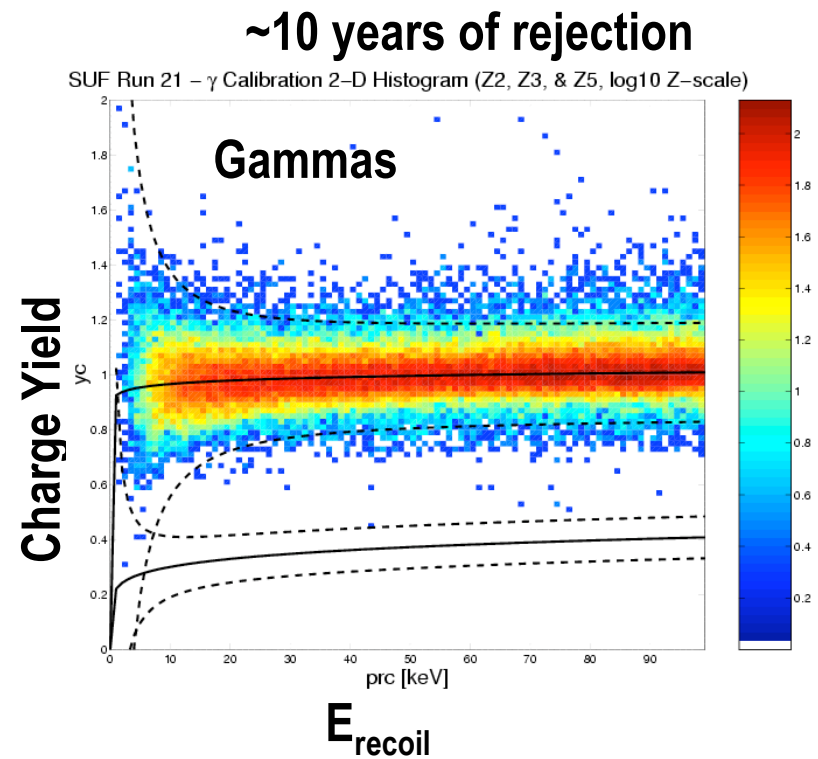
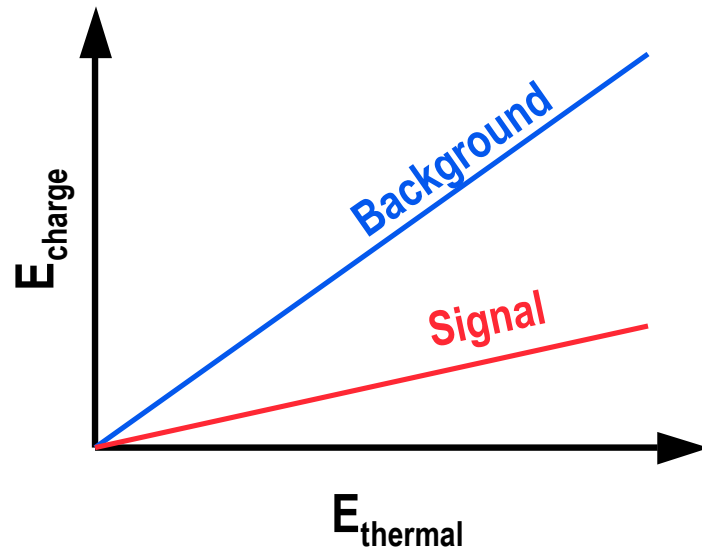


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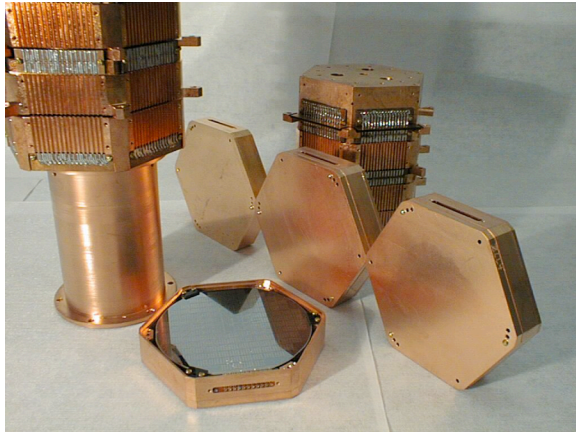
WIMPs 'look' different – recoil discrimination

Photons and electrons scatter from electrons

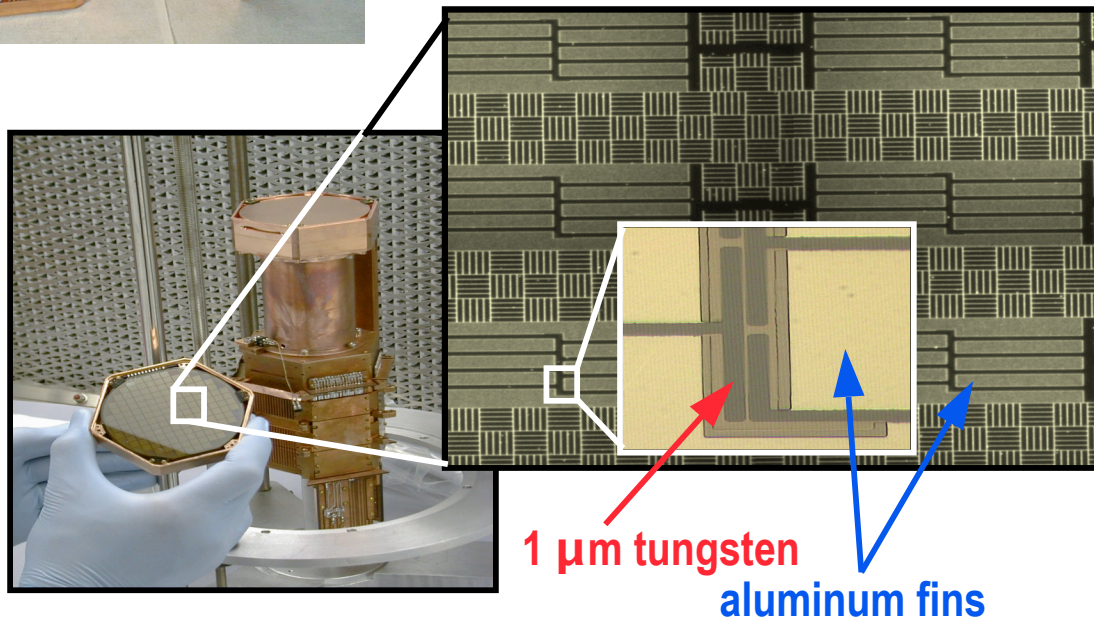
WIMPs (and neutrons) scatter from nuclei



# 'Cryogenic' detectors



- Heat sensitive detectors sensitive to *individual particle interactions*.
- Operated near absolute zero (“cryogenic”)
- Our experiment is called the Cryogenic Dark Matter Search (CDMS)



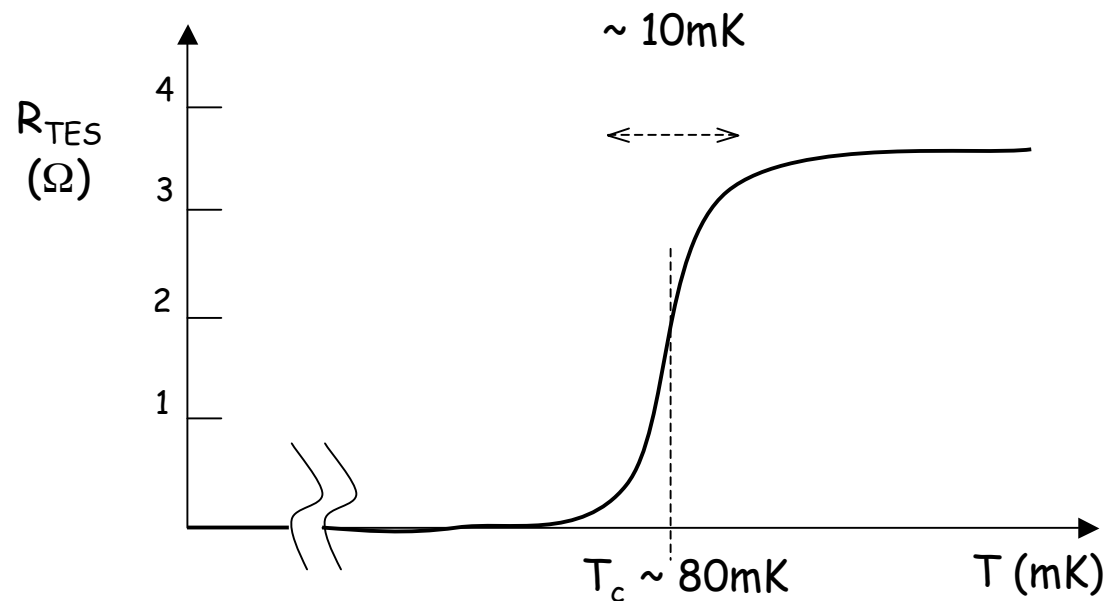
- The detectors are cooled in dilution refrigerators to  $\sim 20\text{mK}$

# Superconducting Films: Ultrasensitive Thermometers

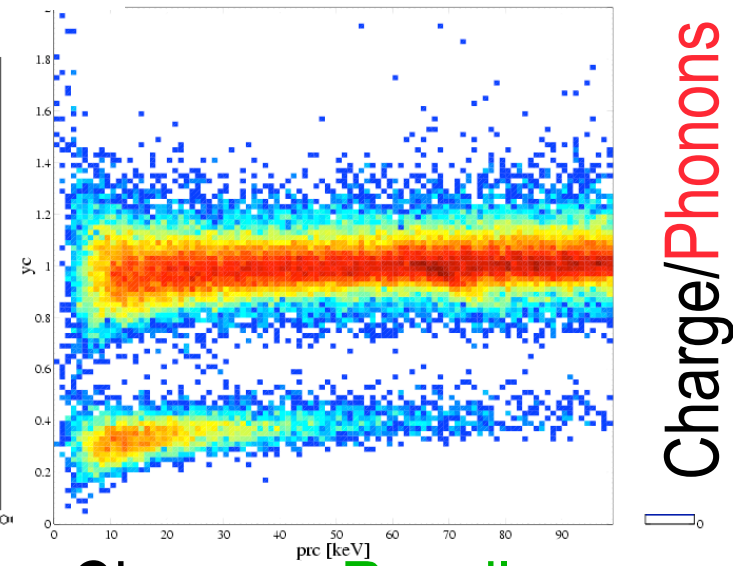
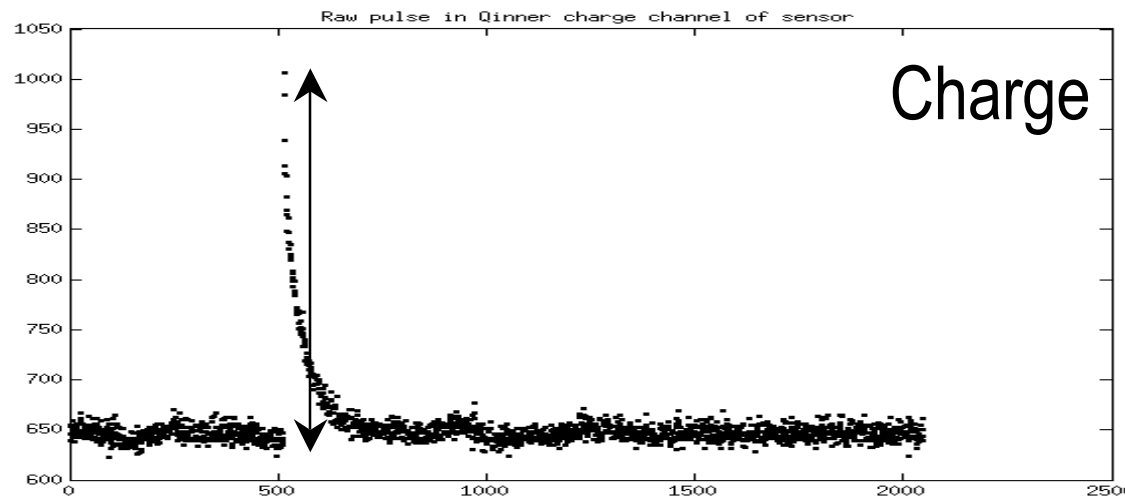
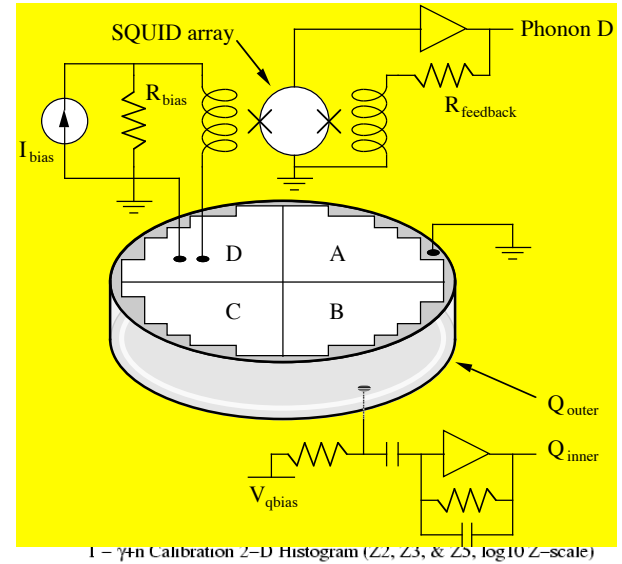
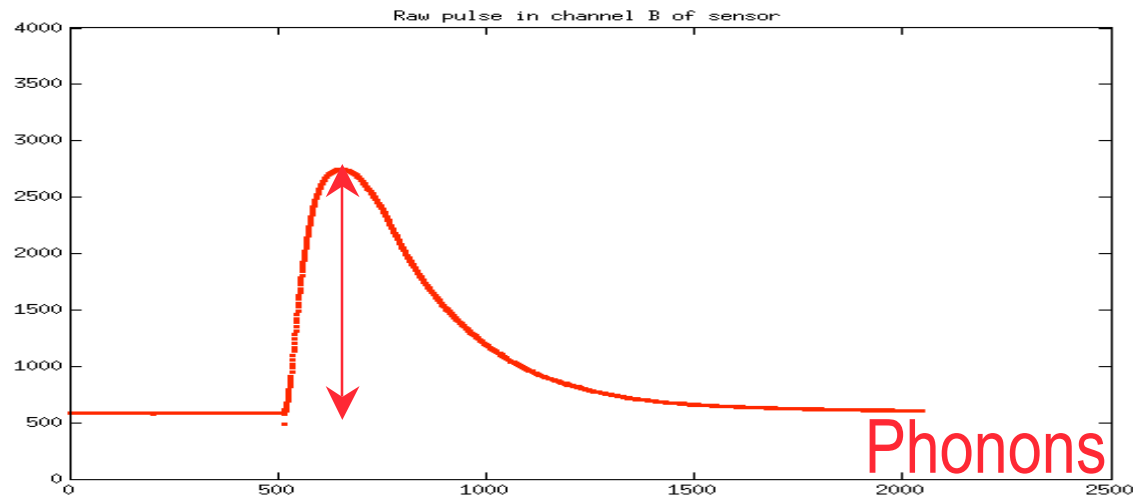
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Superconducting films that detect minute amounts of heat

*Transition Edge Sensor sensitive to fast athermal phonons*



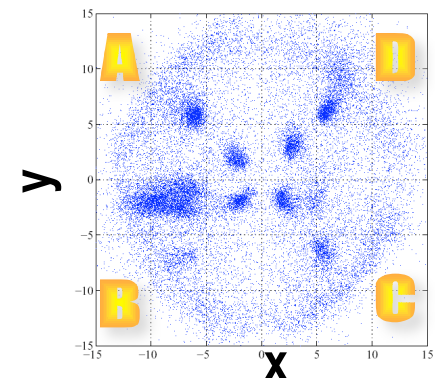
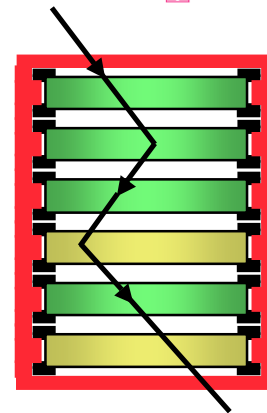
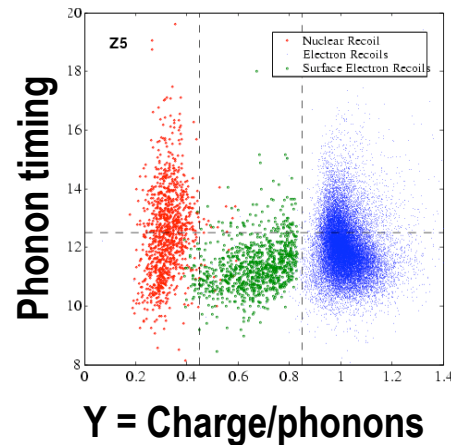
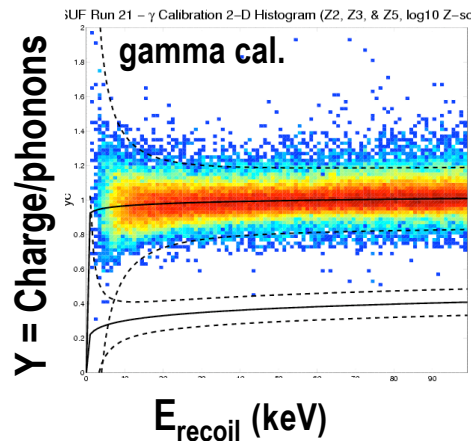
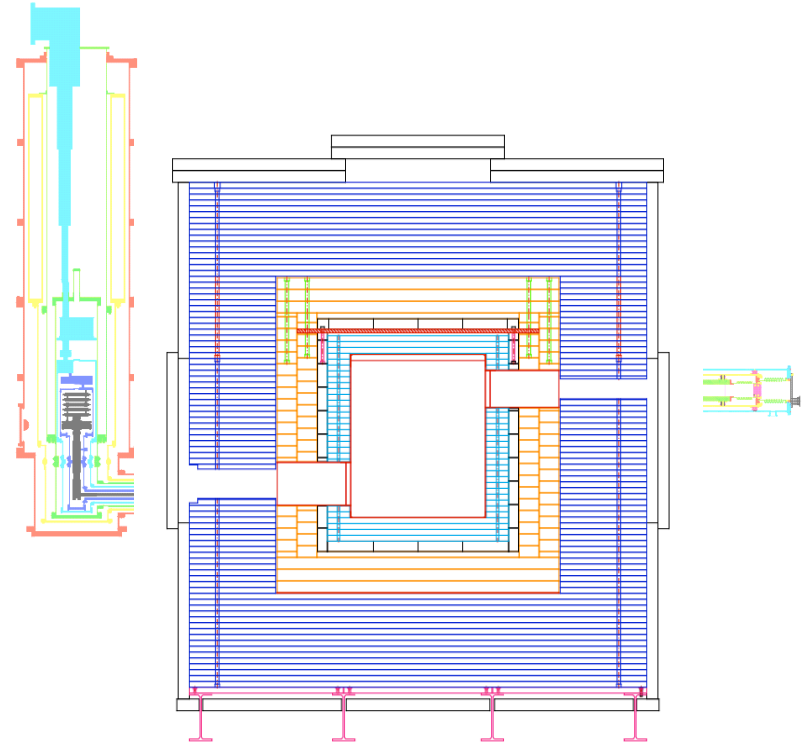
# The Voltages We Measure



Phonons – Charge = Recoil energy

# CDMS Strategy

- ◆ Minimize residual contamination
- ◆ Underground site: hadrons,  $\mu$
- ◆ Muon veto: cosmogenic  $\gamma$ ,  $\beta$ ,  $n$
- ◆ Pb shield:  $\gamma$ ,  $\beta$
- ◆ Polyethylene shield (moderator):  $n$
- ◆ Charge yield:  $\gamma$ ,  $\beta$
- ◆ Phonon-pulse timing: surface events ( $\beta$ )
- ◆ Multiple-scatters:  $n$
- ◆ Silicon vs Germanium:  $n$
- ◆ Position information: optimization/systematics



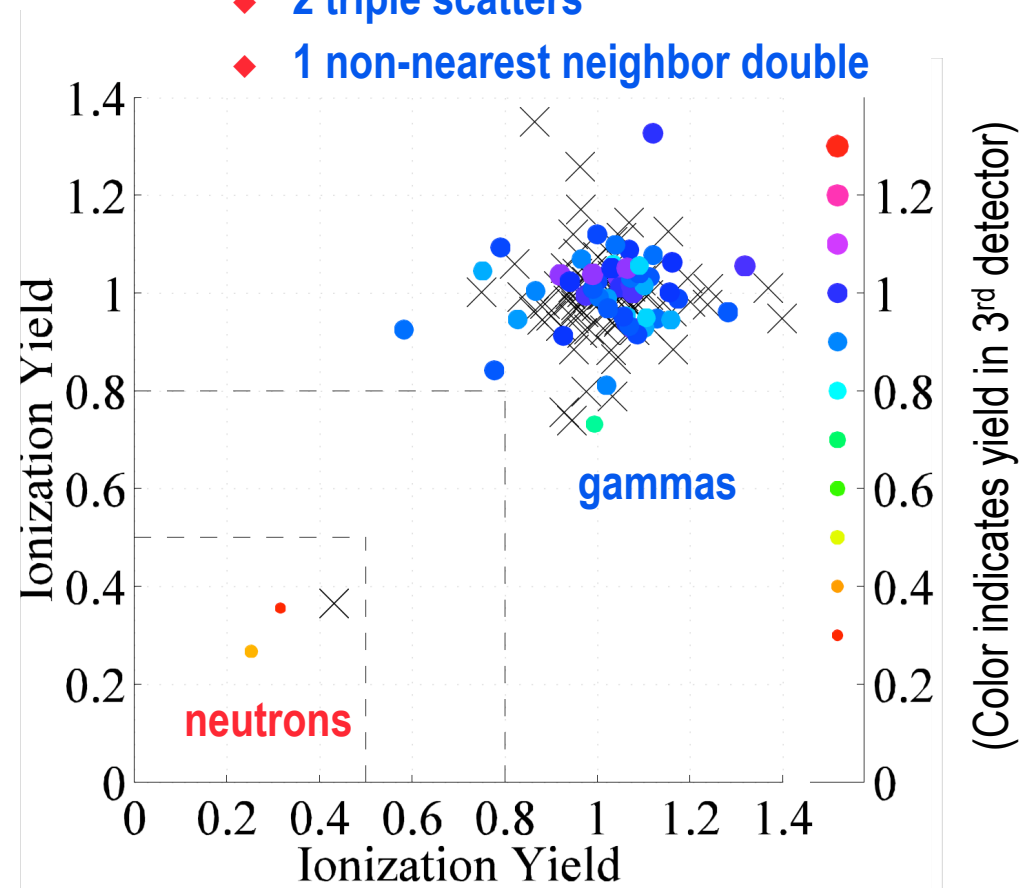
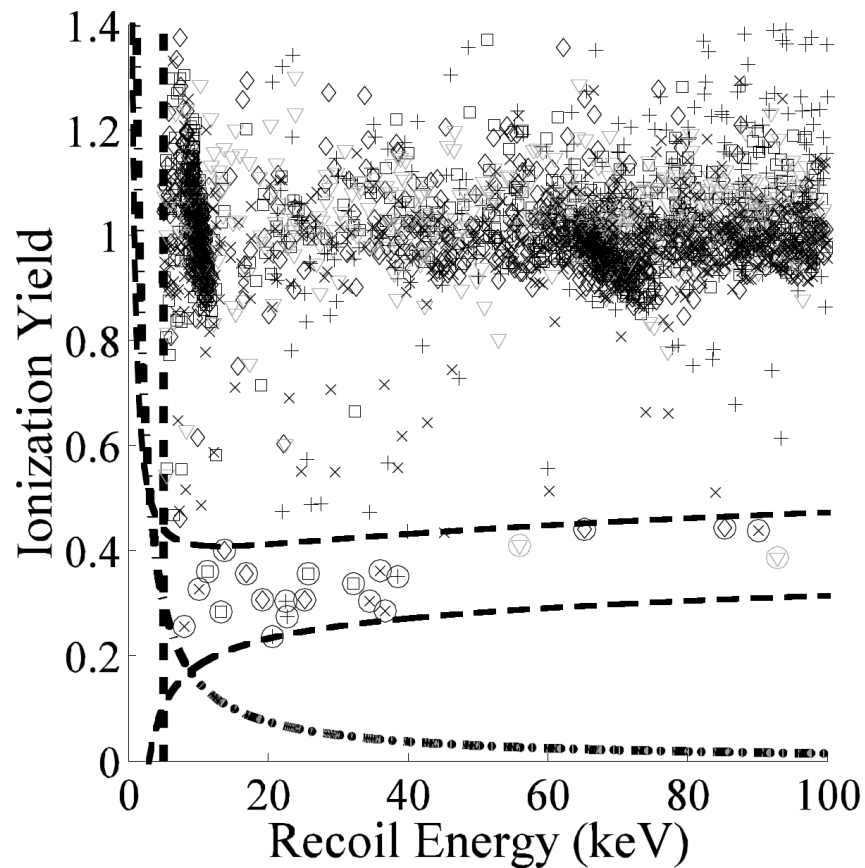
# CDMS Shallow-Site Data

- 28 kg days exposure
- 20 single scatter nuclear-recoil candidates in 4 Ge detectors
- Silicon in grey

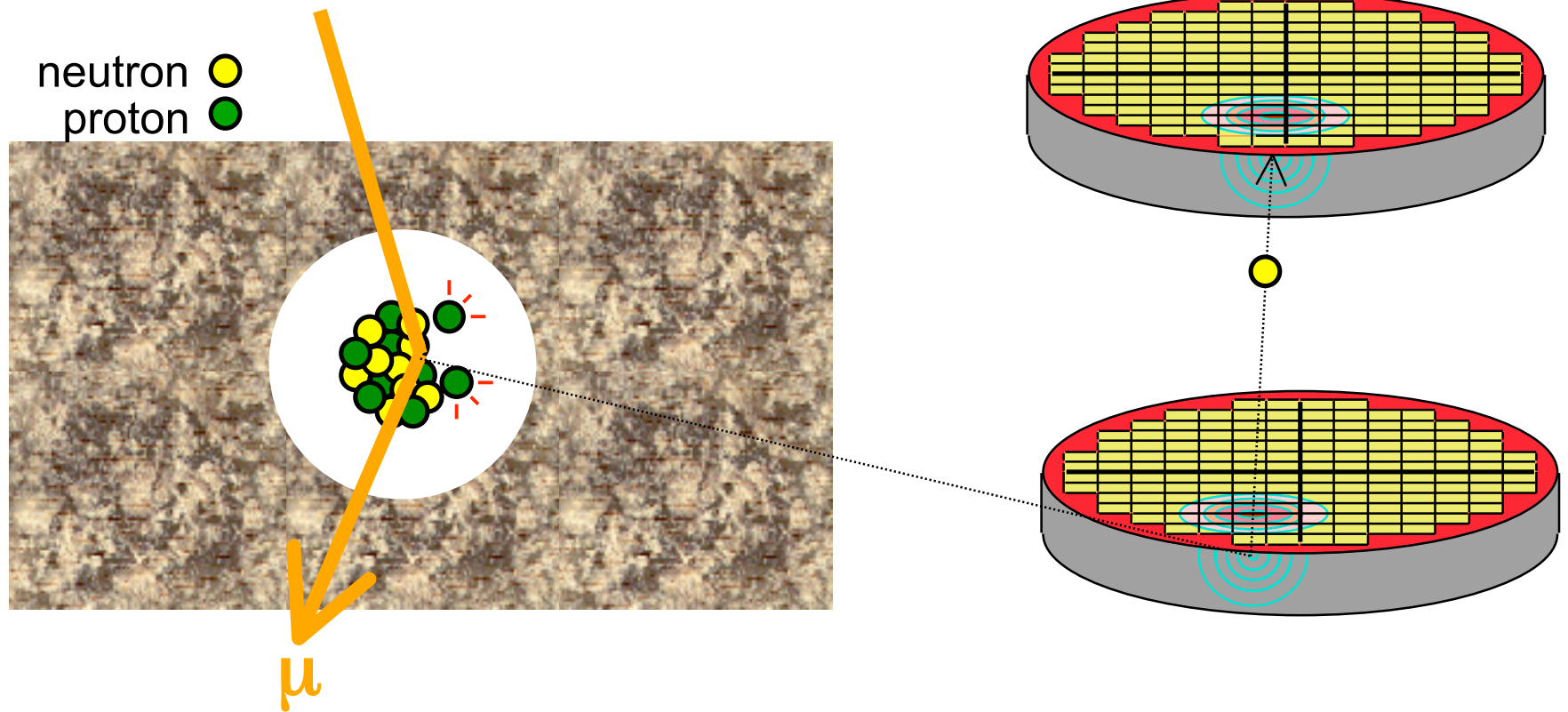
- Non-nearest-neighbor multiples
- Multiple-scatter nuclear recoils estimate neutron contribution to single scatters

♦ 2 triple scatters

♦ 1 non-nearest neighbor double

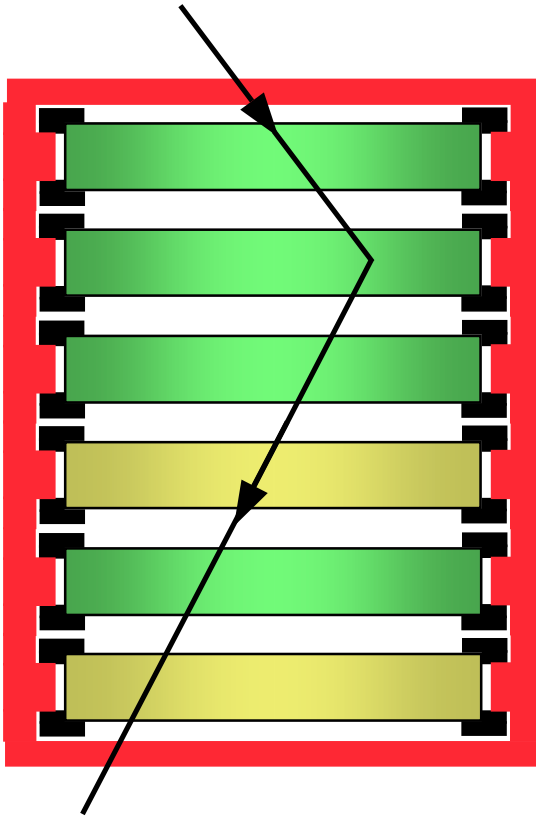


# Those pesky neutrons...

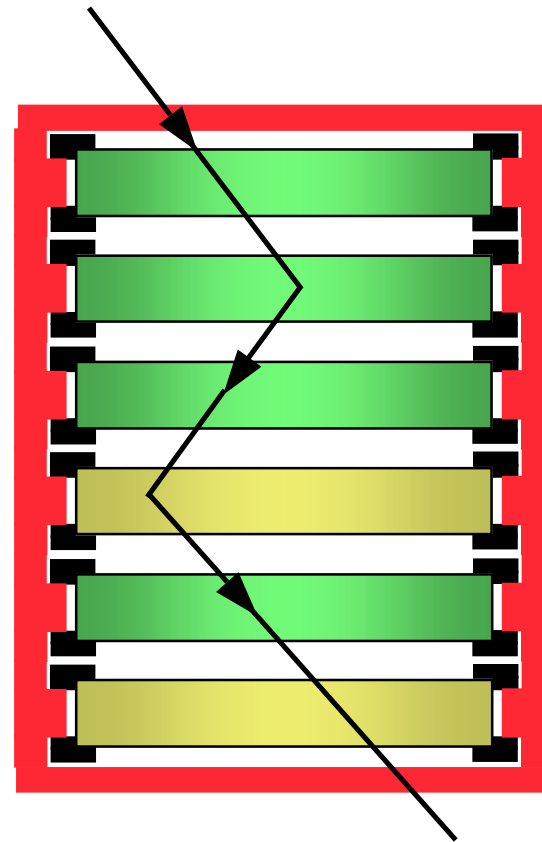


## Neutrons: Single Scatters vs Multiple Scatters

---



Single-scatter nuclear-recoils are produced by WIMPs or neutrons.

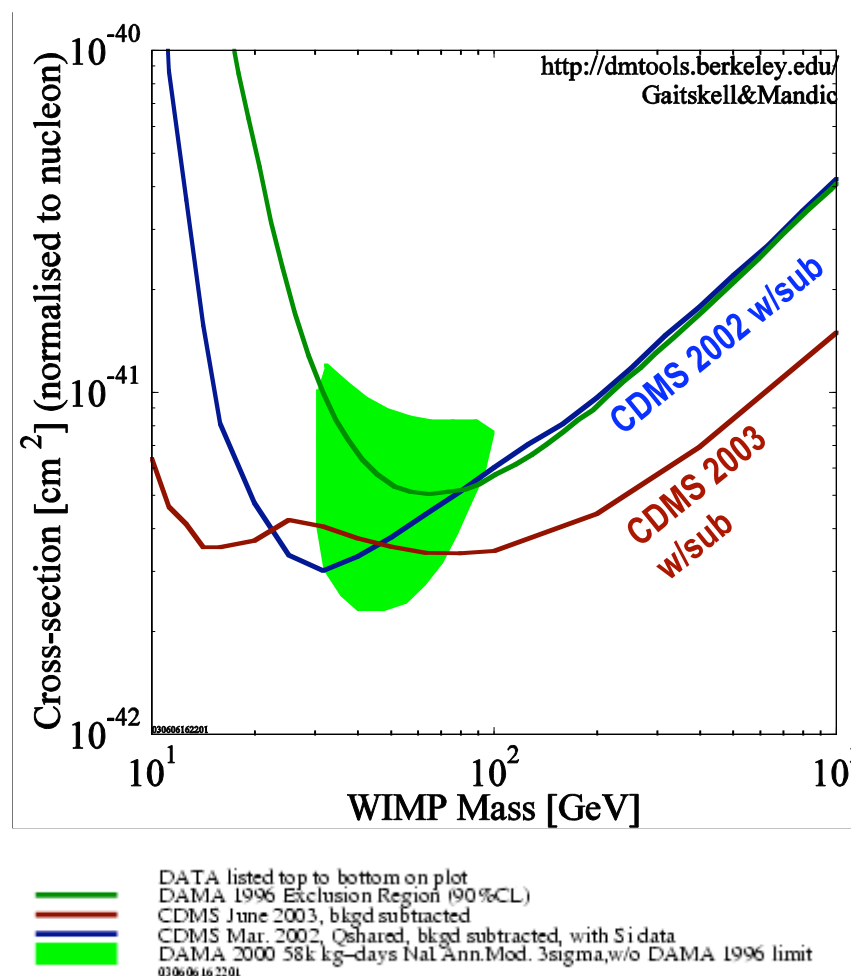


Multiple-scatter nuclear-recoils are only produced by neutrons.

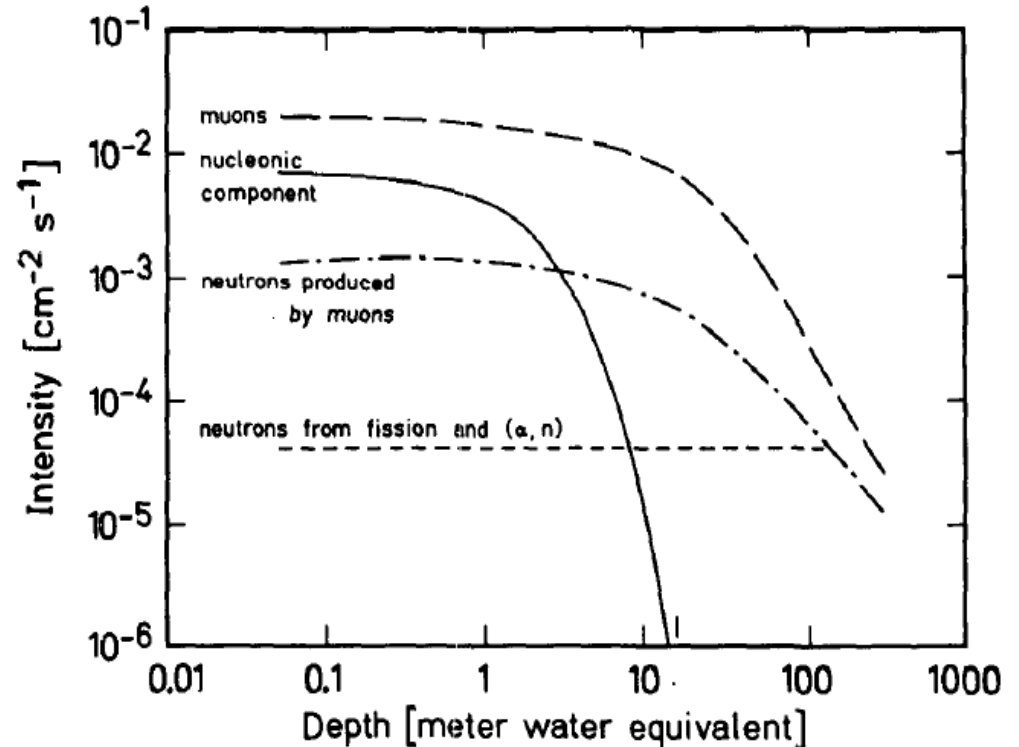
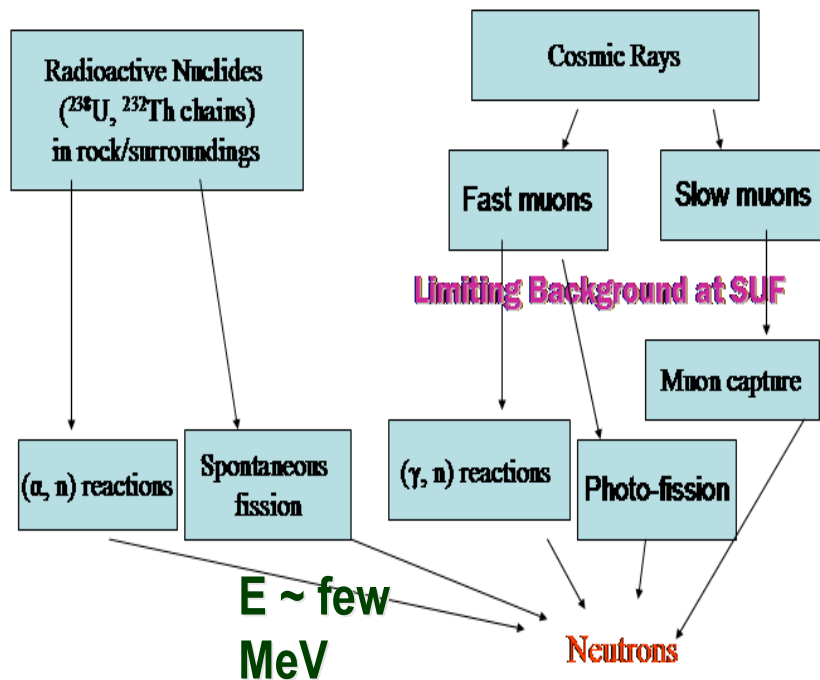
---

## CDMS II – Tower 1 at 17 mwe depth

- 28 kg days exposure
- Neutron rate consistent with
  - ◆ 16 kg-d 'BLIP' run (same site)
  - ◆ 2.3x predicted reduction (increase poly shielding)
- Derive upper limit on WIMP-nucleon cross section:
  - ◆ Apply background 'subtraction' from 'gold plated' multiples
  - ◆ Standard halo
  - ◆  $A^2$  scaling
- Work continues on characterizing electron background
  - ◆ 3V vs 6V charge bias



# The Neutron contribution -- go deep

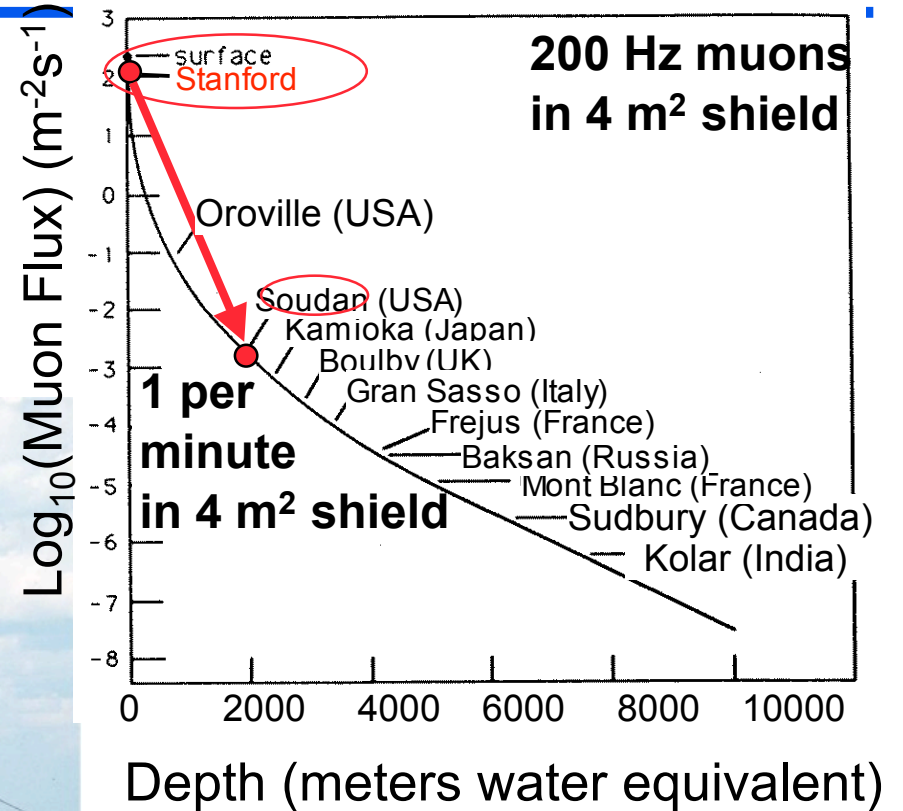


- Strong depth dependence of flux
- At shallow site, muon induced neutrons dominate. High energy  $\mu \Rightarrow n$  ( $E \sim \text{GeV}$ )  
 $\Rightarrow$  Difficult to shield  $\Rightarrow$  Limiting background
- At deep site, n from radioactivity dominates ( $E \sim \text{few MeV}$ )  $\Rightarrow$  shielded

# Getting rid of the neutrons

## CDMS II Deep site at Soudan

- 2100 m.w.e. (713 m deep)
- Muon flux down by 50000x from surface
- Neutron flux down from  $\sim 1/\text{kg/day}$  to  $\sim 1/\text{kg/year}$



# The CDMS II Apparatus

---

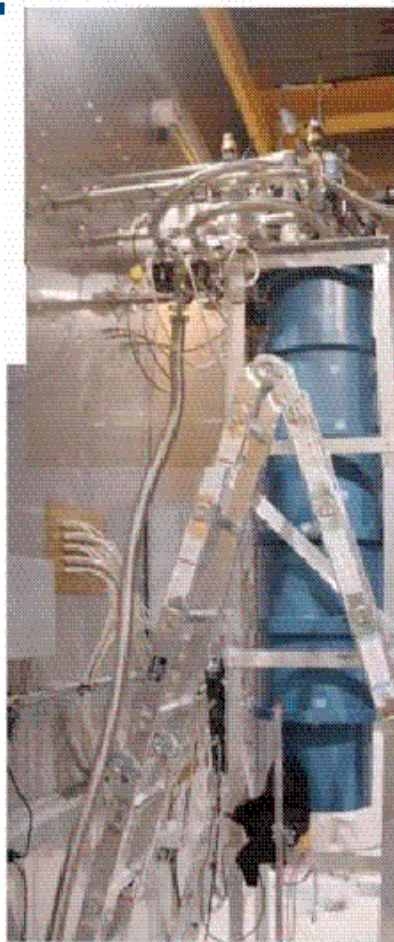


- The Soudan Mine refrigerator includes a low-radioactivity '*clean room*' shielded environment
  - Science data commenced October 2003
  - **Results from first 3 months of running 'Tower 1'**
  - Additional factor of ten by end of 2005
-

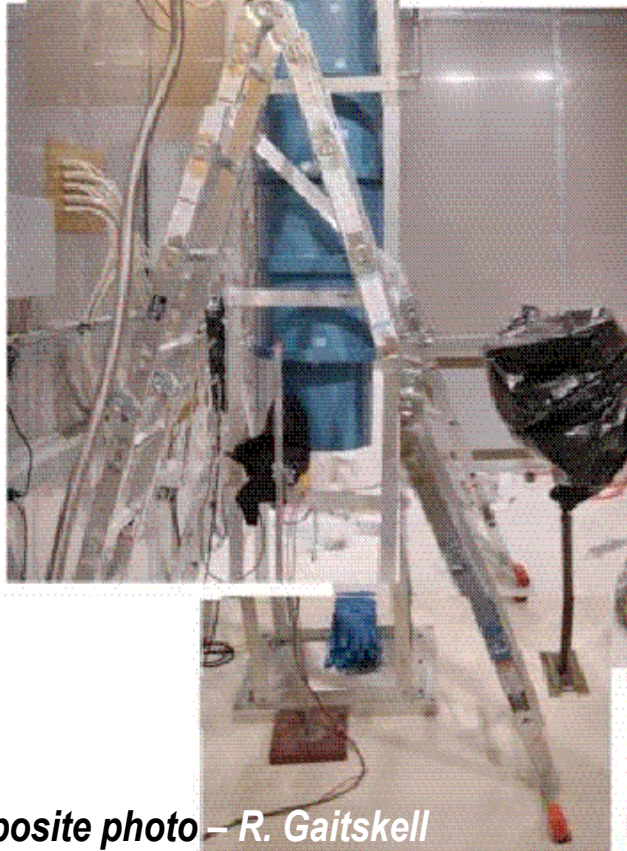
# **Soudan Mine CDMS Icebox & Dilution Fridge**

**March 2002**

**Upper poly & Pb shield will  
be winched into place**



**Dilution  
fridge used  
to achieve  
20 mK base  
temperature  
at centre of  
Icebox**

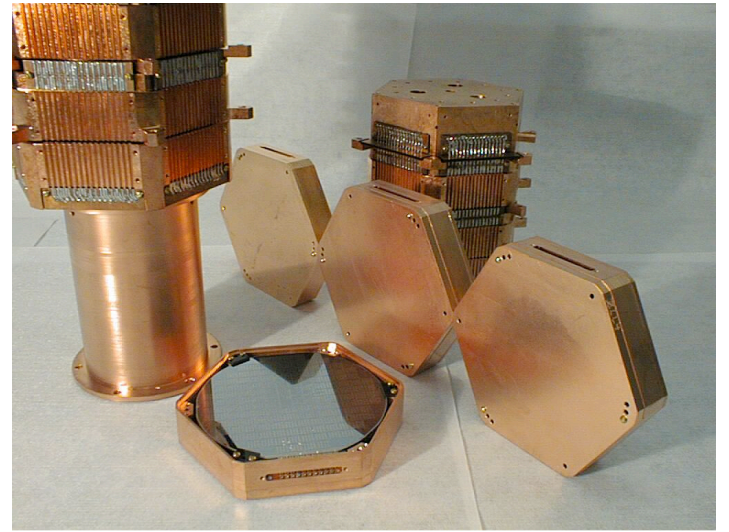
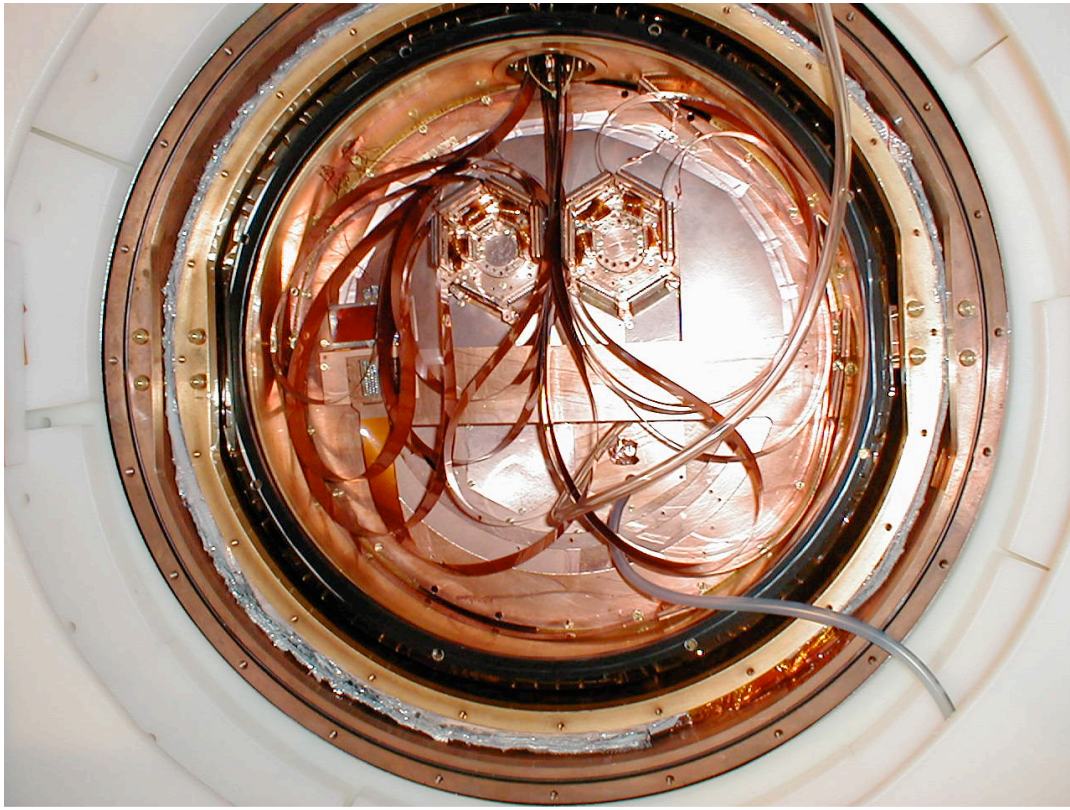


**Icebox assembled including  
polyethylene and Pb shield  
...now awaiting attachment  
to dilution fridge**

**Clean Room at depth of  
2341 ft**

**Composite photo – R. Gaitskell**

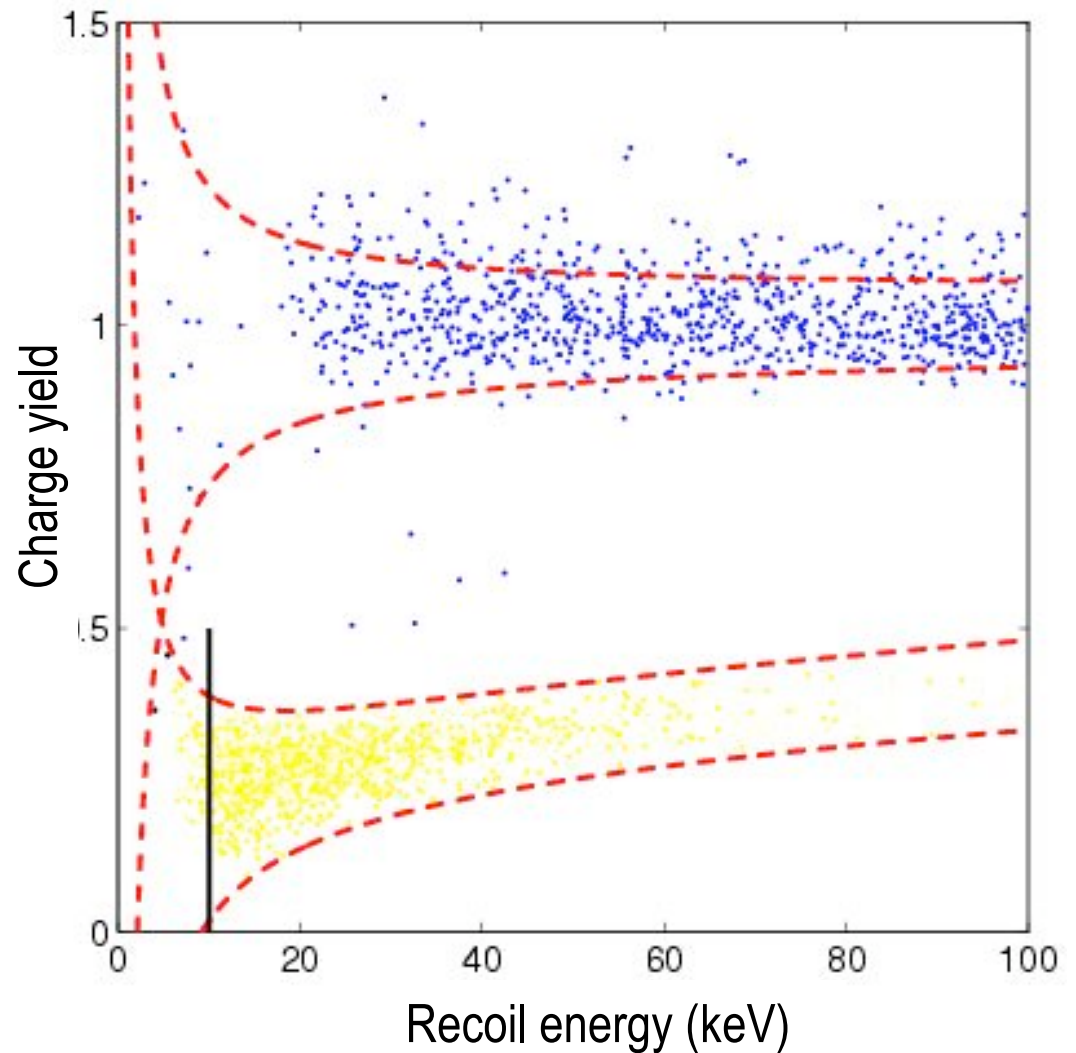
# Tower 1 and Tower 2 in Soudan



# WIMP search data with Ge detectors

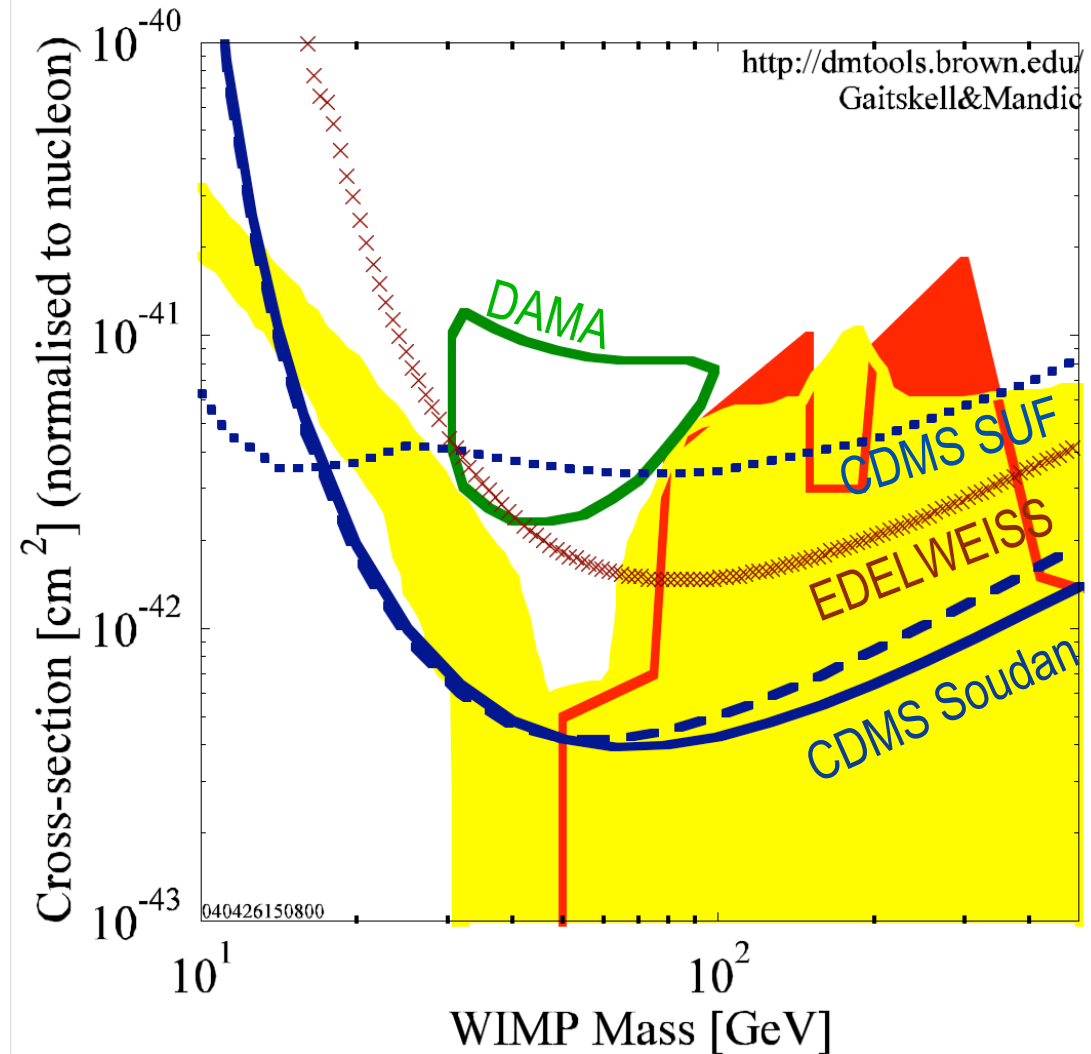
- **Exposure**
  - ◆ 92 days (October 11, 2003 to January 11, 2004)
  - ◆ 52.6 live days
  - ◆ 20 kg-d net (after cuts)
- **Data: Yield vs Energy**
  - ◆ Blind analysis - event selection determined by calibration data
  - ◆ Yellow points from neutron calibration

**No nuclear-recoil  
candidates**



# NEW CDMS limit from Soudan

- Exposure after cuts of 52.6 kg-d raw live exposure with  $Ge = 19.4$  kg-days for  $60 \text{ GeV}/c^2$  WIMPs
- No nuclear-recoil candidates
- Expect  $0.7 \pm 0.4$  misidentified betas
  - ♦ Second non-blind analysis has 1 candidate
- Expect  $0.05 \pm 0.02$  unvetoed neutrons (0.7 muon coincident neutron)
- New limit ~4x better than EDELWEISS at a WIMP mass of  $60 \text{ GeV}/c^2$

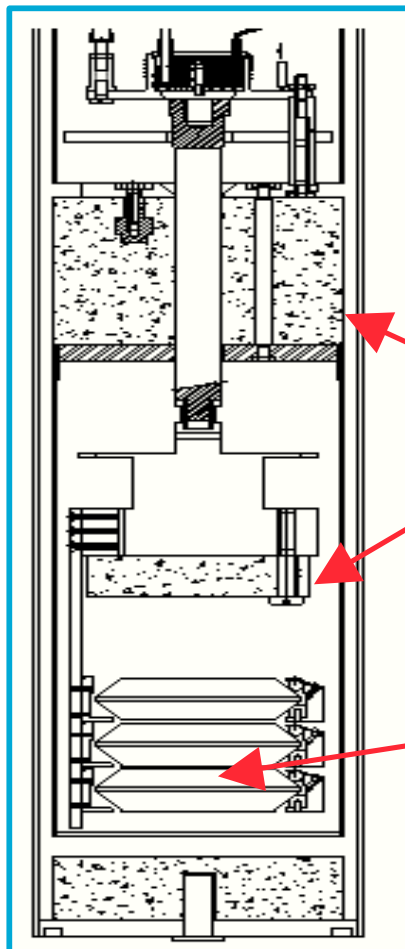


10x more sensitivity in 2005

*astro-ph/0405033*

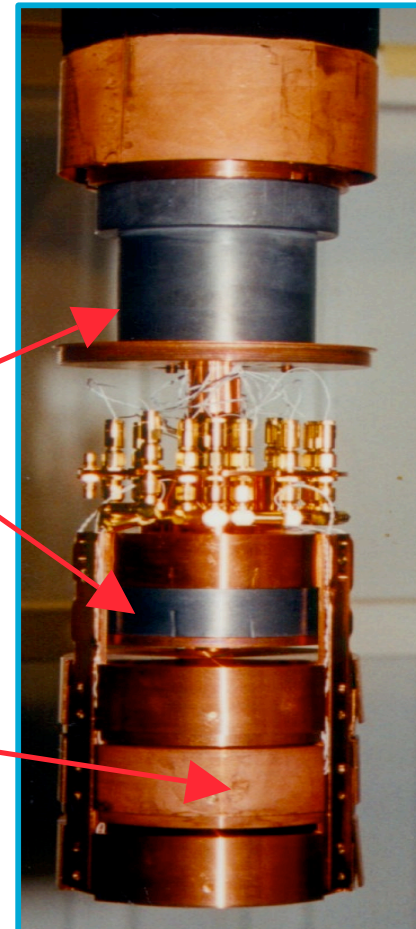
## Edelweiss-I in Frejus Tunnel: “1 kg” stage

- First data taking in Fall 2000 at 4800 mwe depth
- Detector improvements: 2nd data set early 2002
- 3rd data taking: October 2002 - March 2003



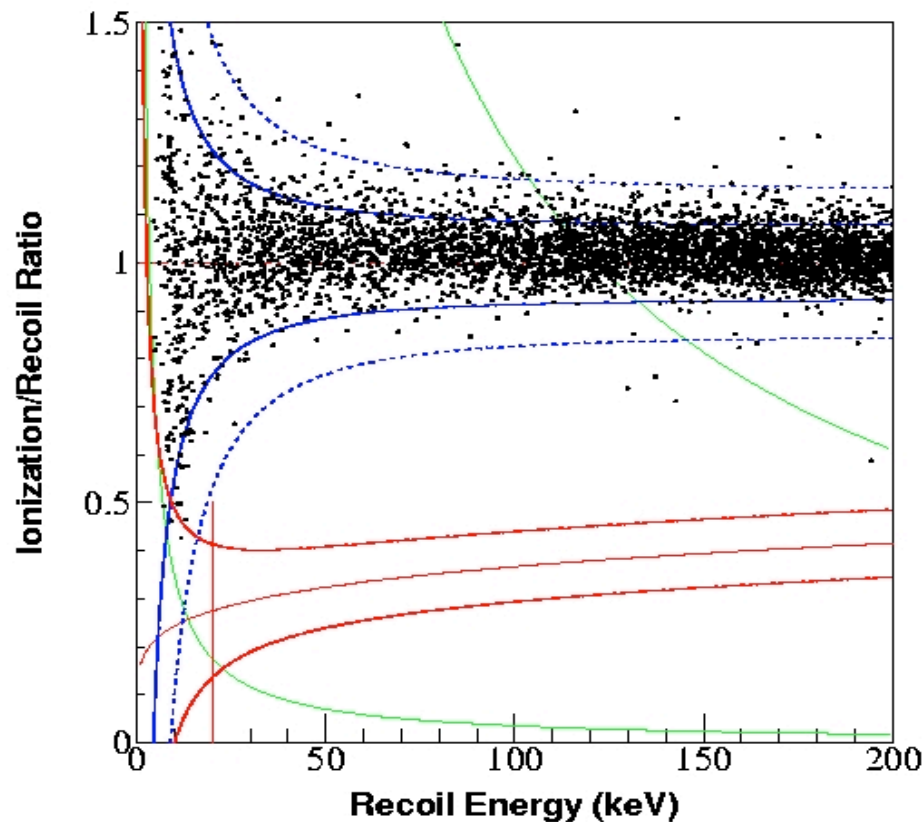
Archeological  
lead

3 \* 320 g Ge detectors:  
heat and ionization  
simultaneous readout  
(NTD thermistor)  
Installed May 2002

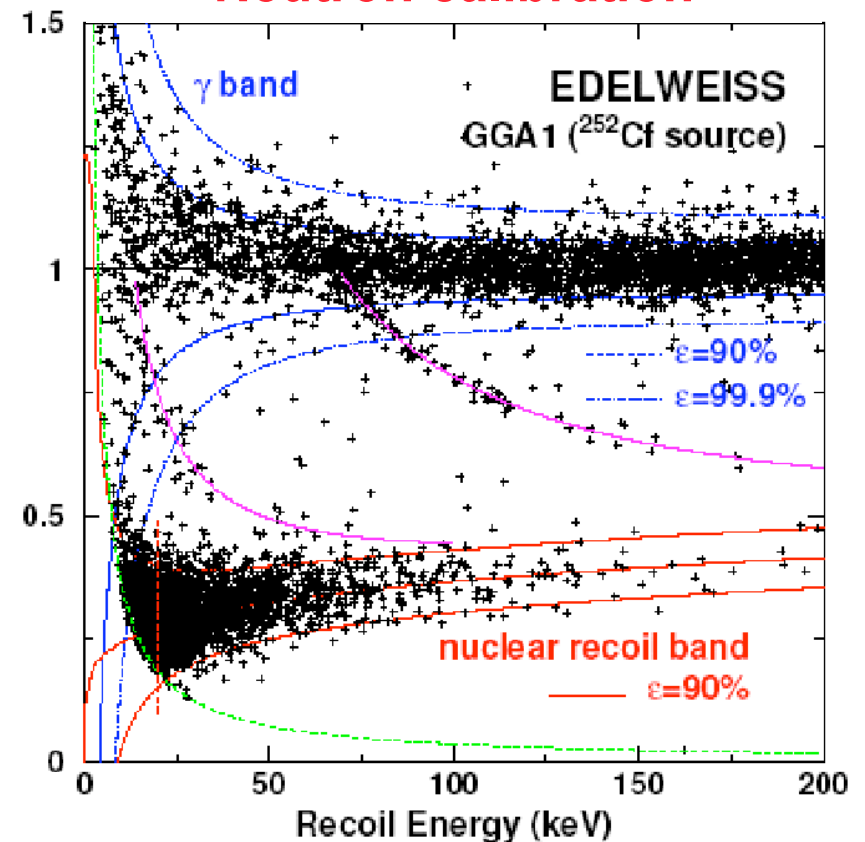


# Edelweiss-I: Recoil discrimination

## Gamma calibration

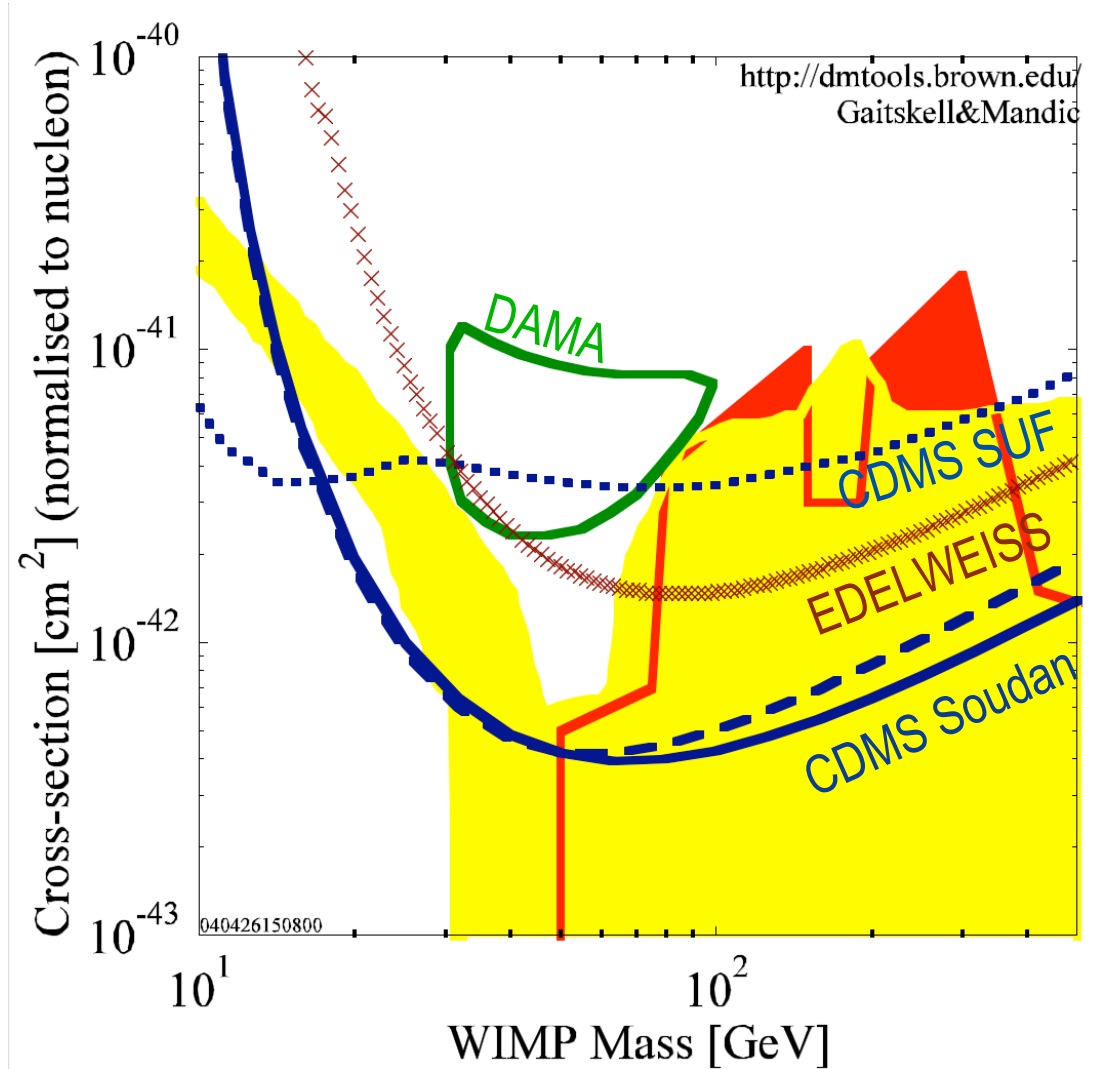


## Neutron calibration

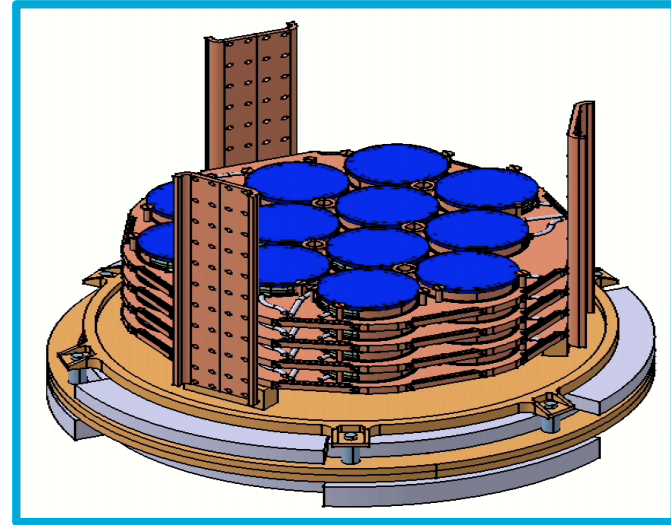
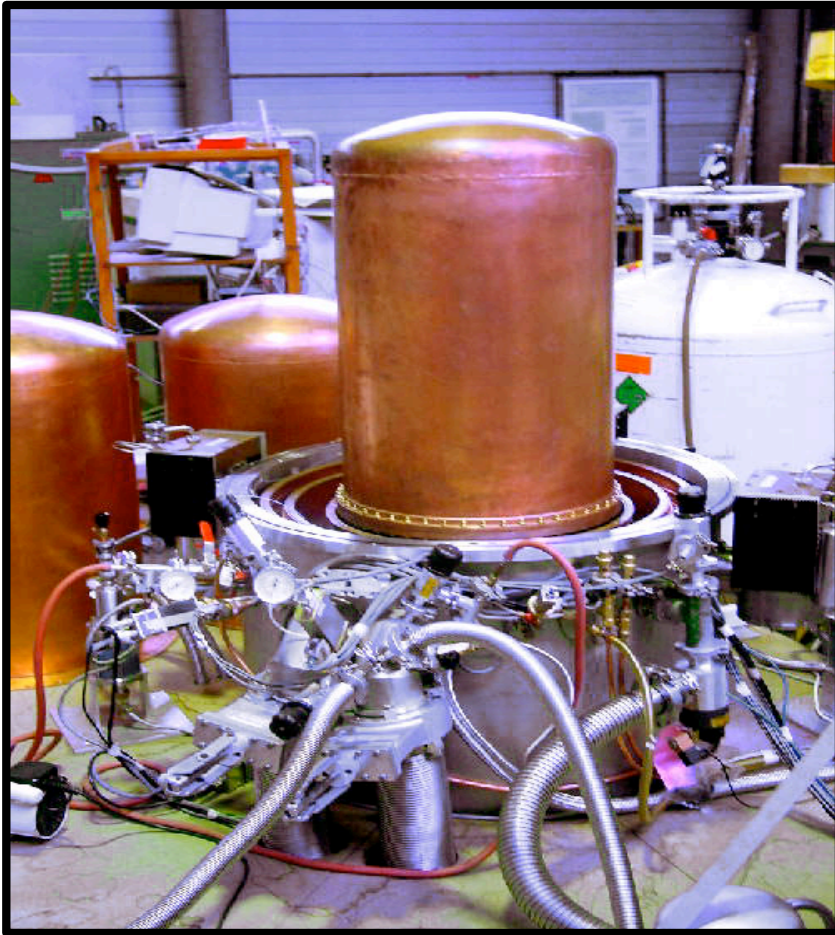


**Nuclear recoil discrimination down to 20 keV threshold**  
 **$\gamma$ -ray rejection > 99.99 %**

# Edelweiss



## Edelweiss-II

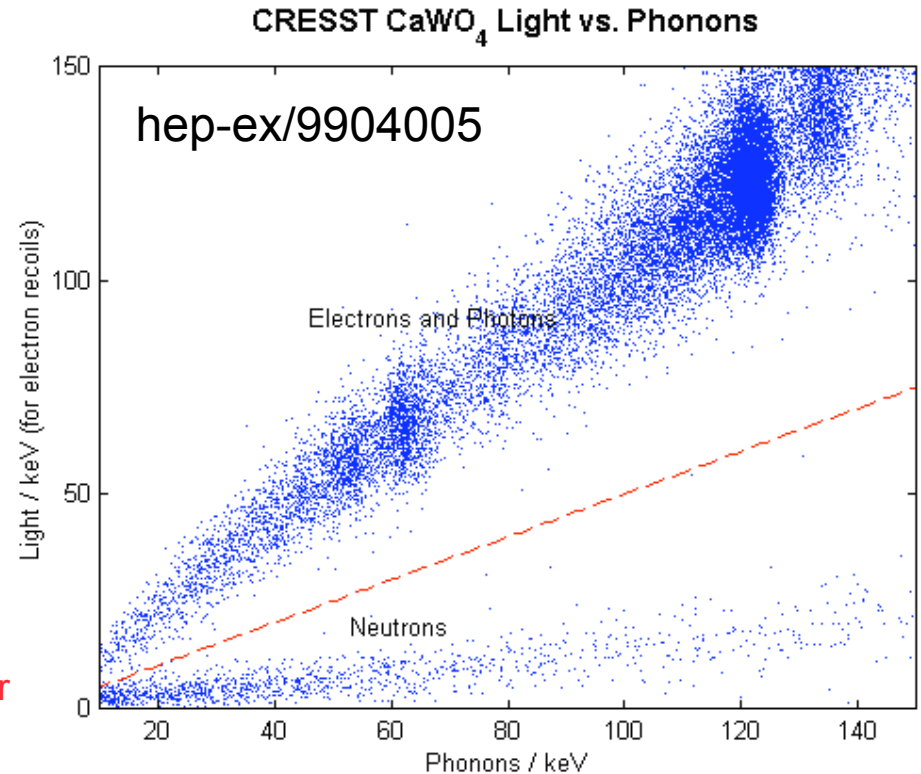
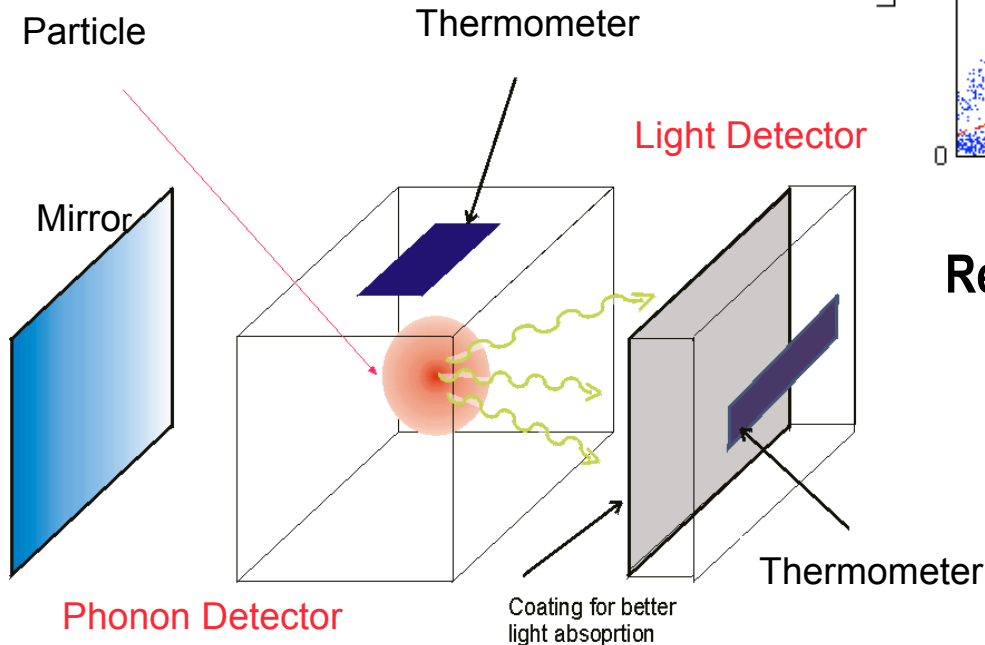


- September 2003: end EDELWEISS-I
- Install EDELWEISS-II with 28 x 320-g Ge detectors
- 100 detector capacity

*Dilution : 8-10 mK obtained on several runs*  
*Wiring and cold electronic test : summer 2003*

# CRESST: Phonons and Scintillation

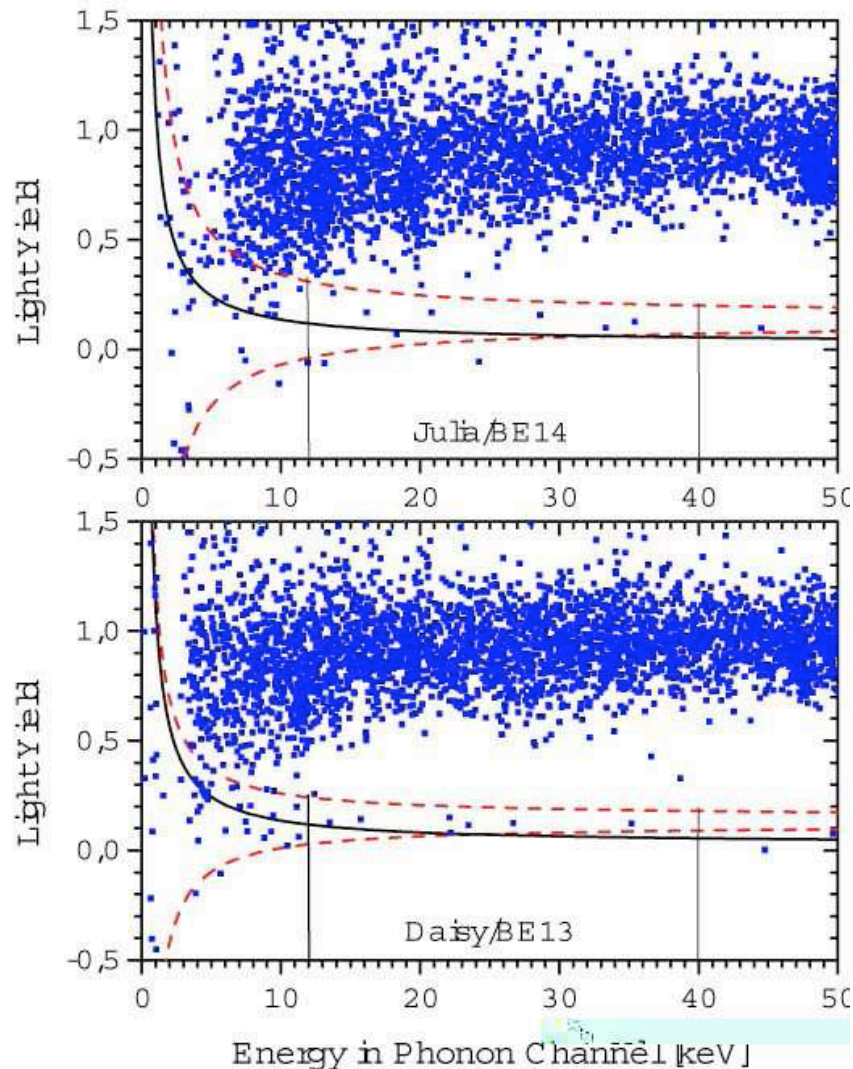
- Nuclear recoils have much smaller light yield than electron recoils
- Photon and electron interactions can be distinguished from nuclear recoils (WIMPs, neutrons, ...)



## Results from a 6g $\text{CaWO}_4$ prototype

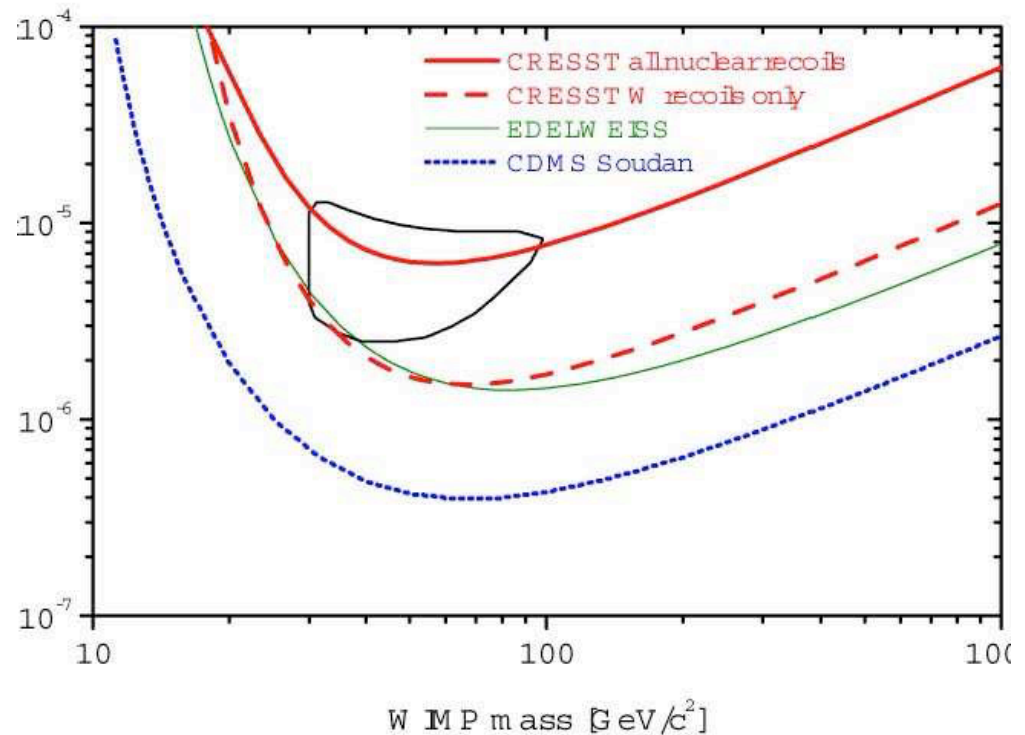
- ◆ No problem from surface electrons
- ◆ Very small scintillation signal
  - Scintillation threshold will determine minimum recoil energy
- ◆ Data run with 2 x 300g detectors

# CRESST: Phonons and Scintillation



This just out...20 kg-d exposure

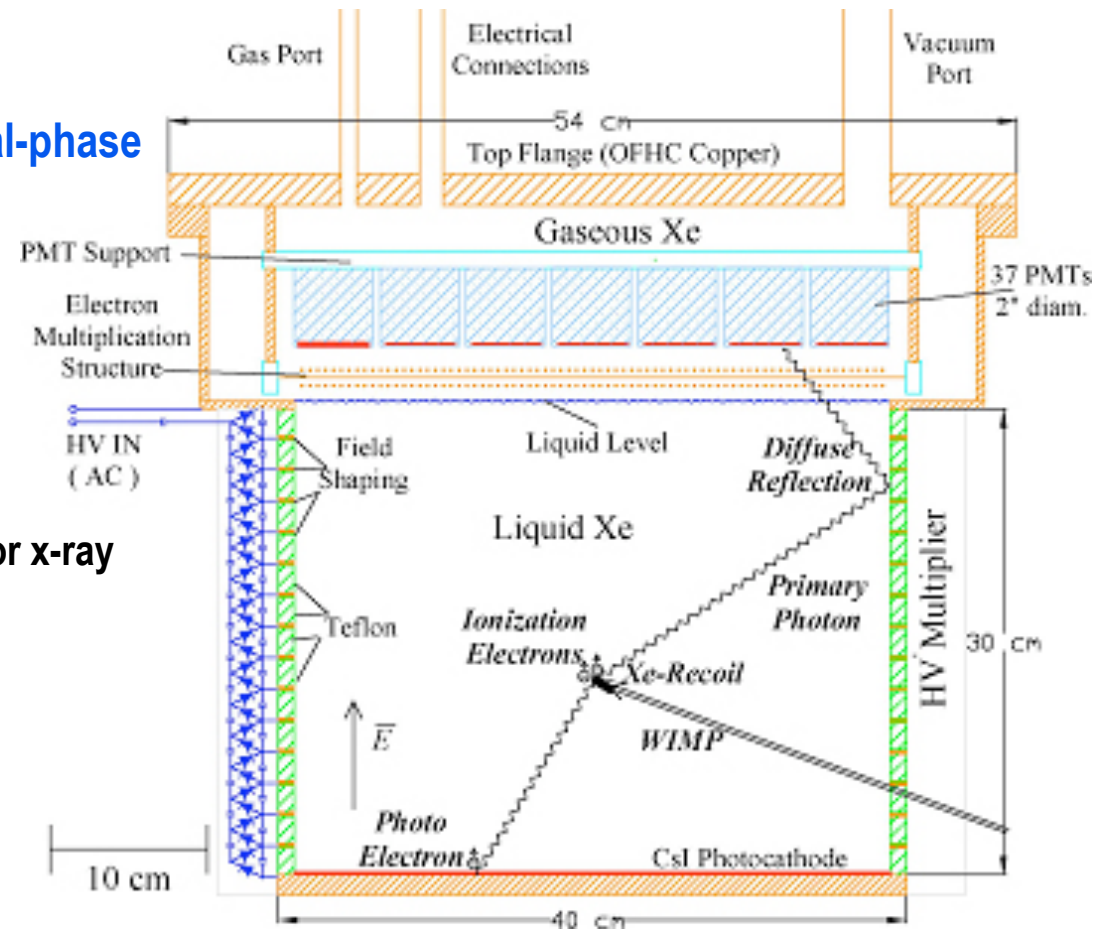
- Low energy neutron background (no shielding)
- Assumed to be oxygen-neutron recoils and separate lower-yield region for tungsten



astro-ph/0408006

# Liquid Xenon Detectors

- Potential to challenge cryogenic detectors
  - ◆ Background rejection (PSD, dual phase)
  - ◆ Scales more readily to high mass
- Challenges of Liquid Xenon
  - ◆ Ionization for nuclear recoil in dual-phase
  - ◆ Low threshold
- Two major programs
  - ◆ Zeplin (UK/UCLA et al)
  - ◆ XENON expt (Columbia et al)
    - R&D phase I study
    - Based on earlier developments for x-ray astrophysics

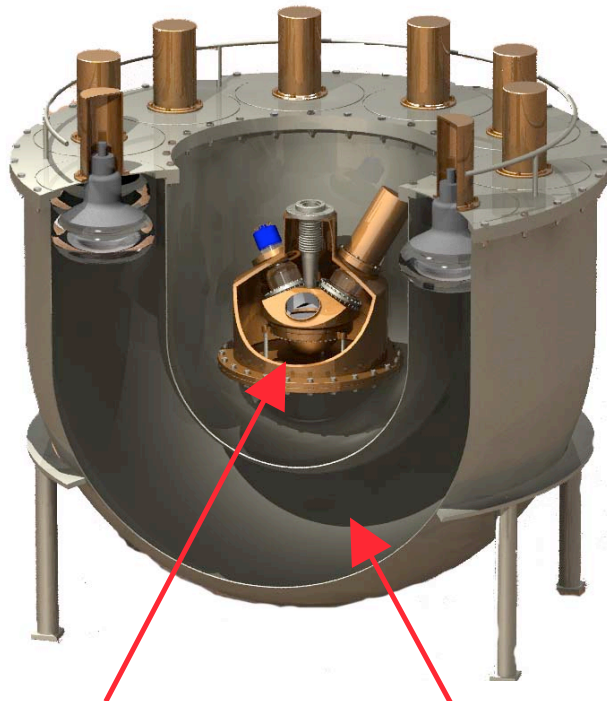


Columbia Univ.

# Boulby Dark Matter Collaboration: Zeplin I

## •Single-phase detector

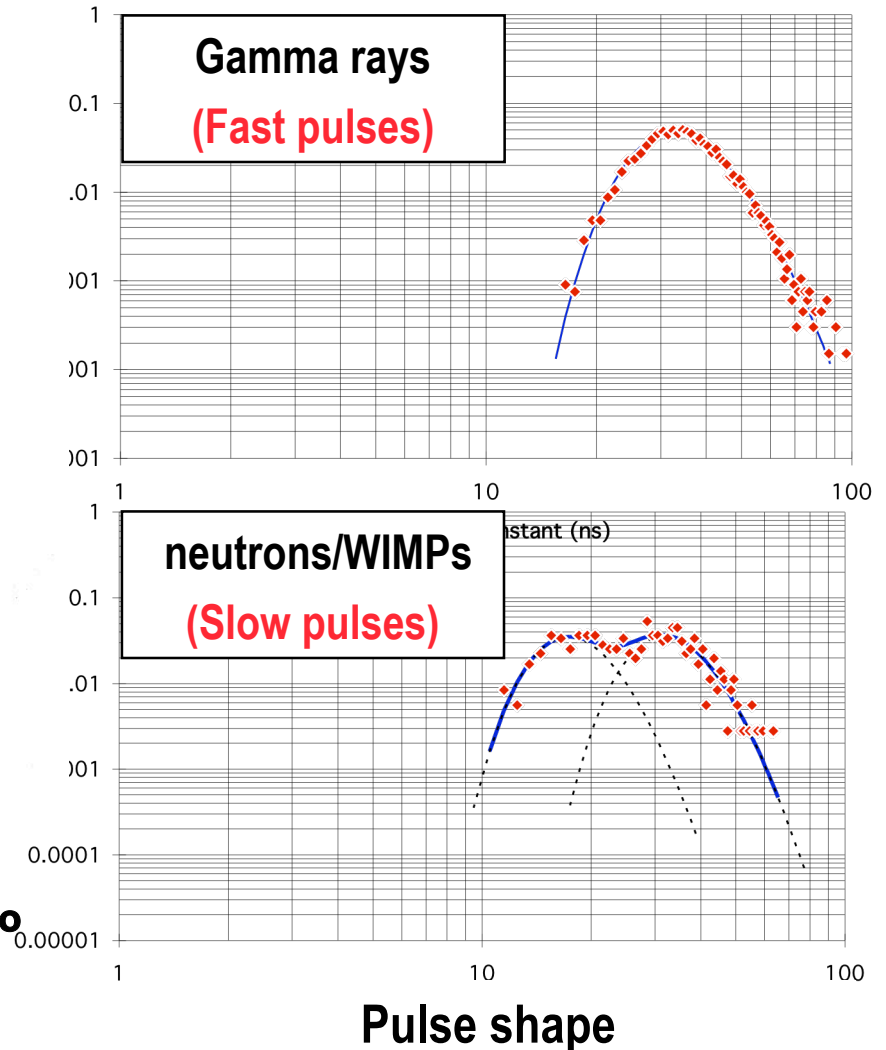
- ◆ Measure primary scintillation
- ◆ Pulse shape discrimination



5kg LXe target (3.1 kg fid)  
3 PMTs  
Cu construction  
Polycold cryogen cooling

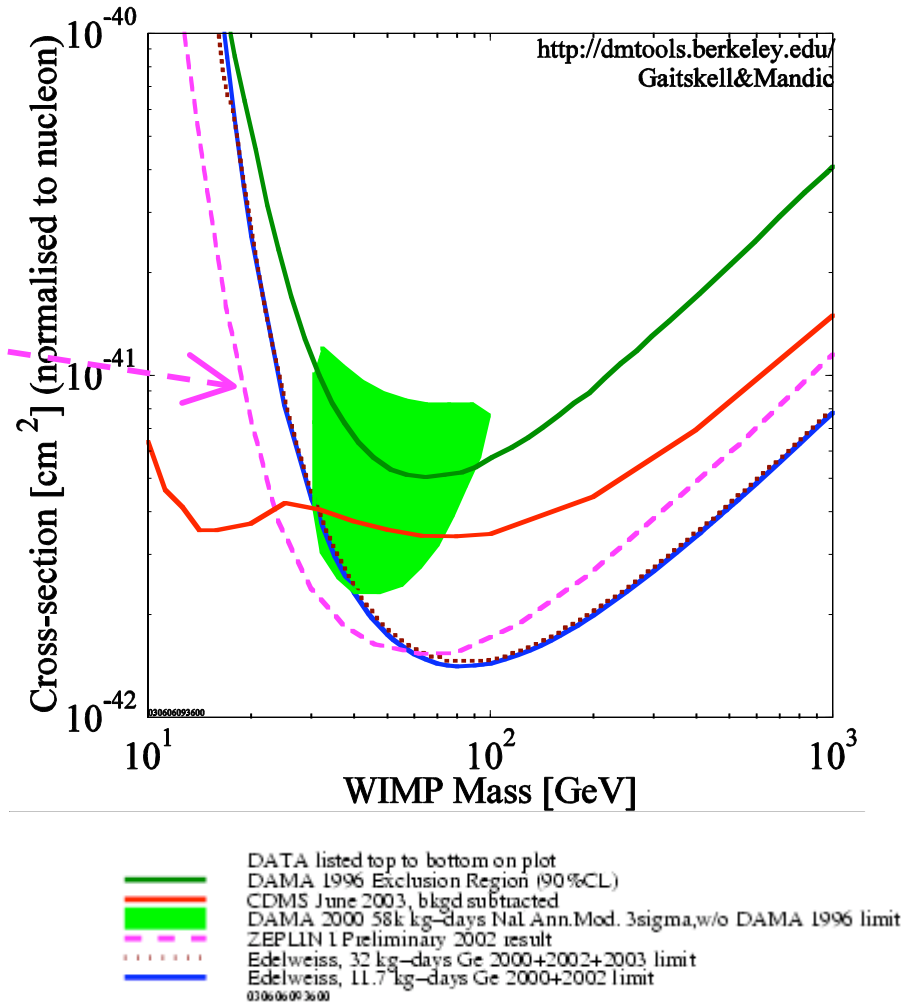
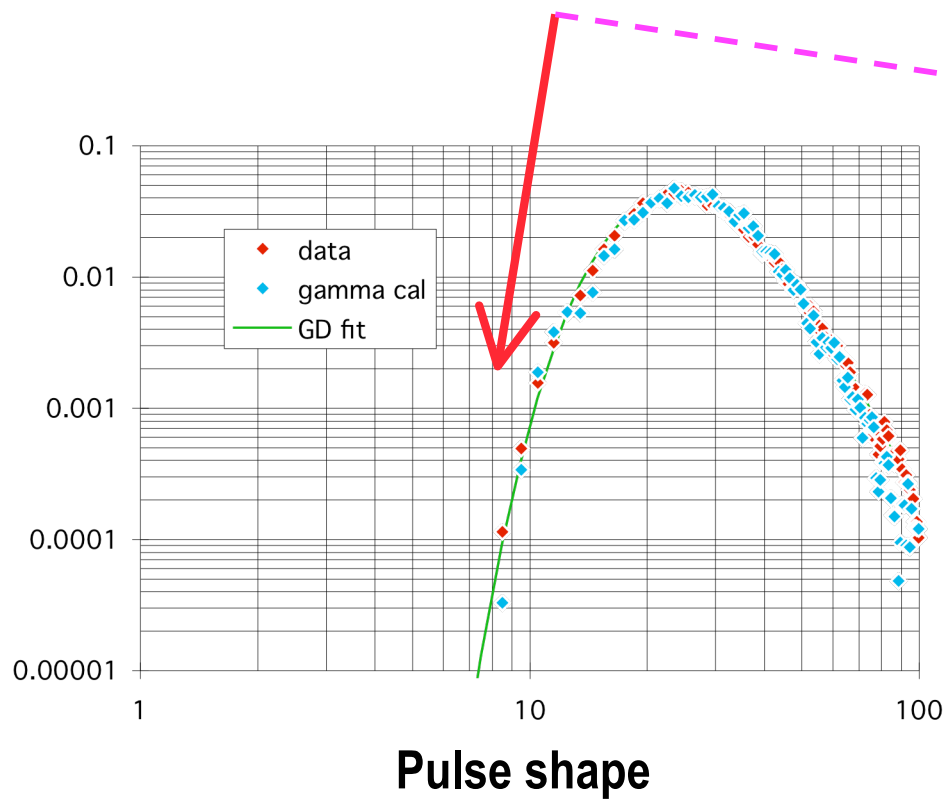
1 tonne Compton veto  
PMT background tag  
Gamma calibration  
Neutron monitor

## *Discrimination parameter*



# ZEPLIN I Data Run

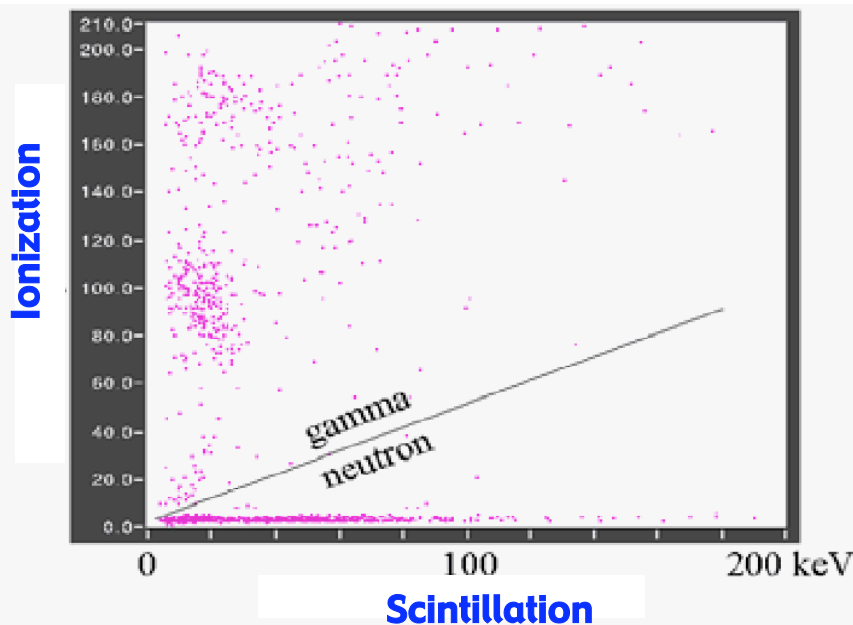
- 75 days live time, 230kg-days data
- Gamma calibration veto events
- WIMPs: Look for excess of events in tail region due to nuclear recoils



# Zeplin II, III – improve discrimination

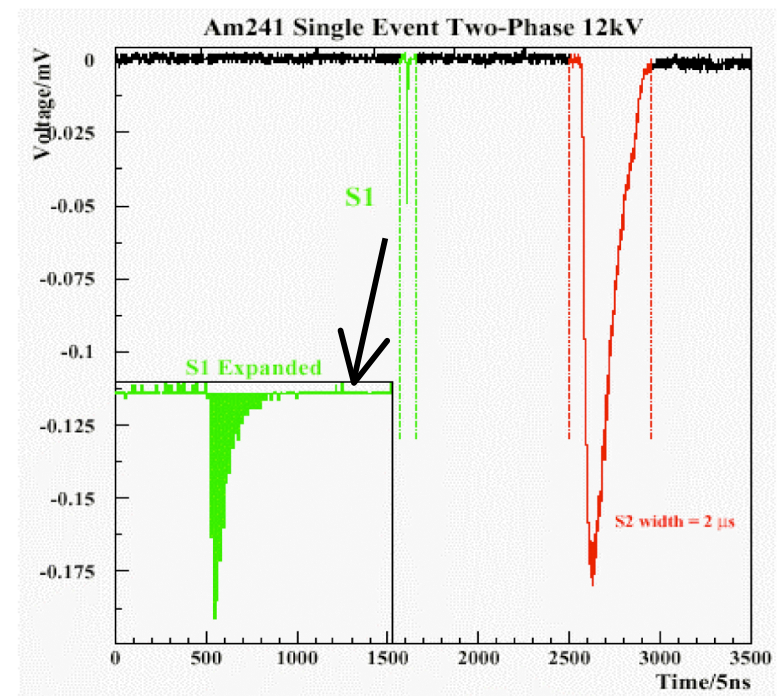
## • Zeplin II: 2-phase detection

- ◆ Development of 2-phase detector demonstrated in 1-kg prototype
- ◆ Construction and commissioning underway of Zeplin II (30kg active)
  - Low-field – no ionization for nuclear recoils
- ◆ Xe-gas tested -- observed electro-luminescence; fill LXe next...



## • Zeplin III: High-field readout

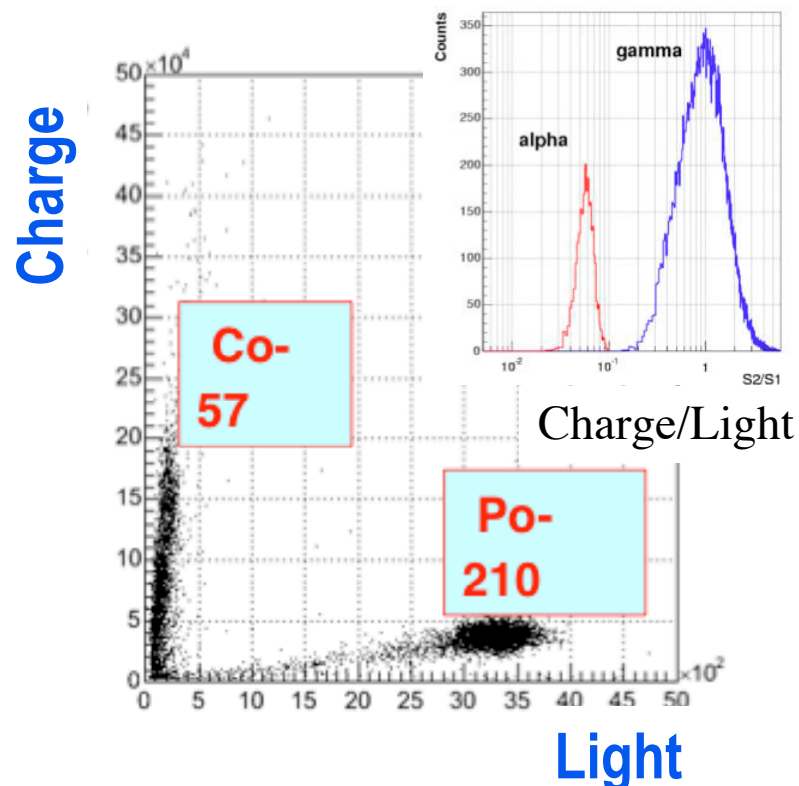
- ◆ 8kV/cm field reduces ionization recombination for nuclear recoils
  - Demonstration with alpha source
  - Limits fiducial volume to 3.5cm depth = 6kg active target
- ◆ Under construction



# XENON Collab. results with 1.5 kg prototype

- Electron drift length  $> 1$  m
- Stable 2-phase operation.
- Light collection poor: 0.3 p.e./keV

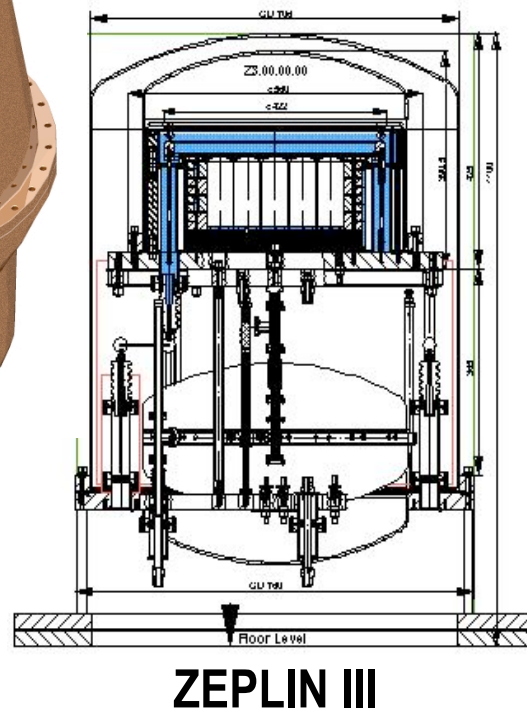
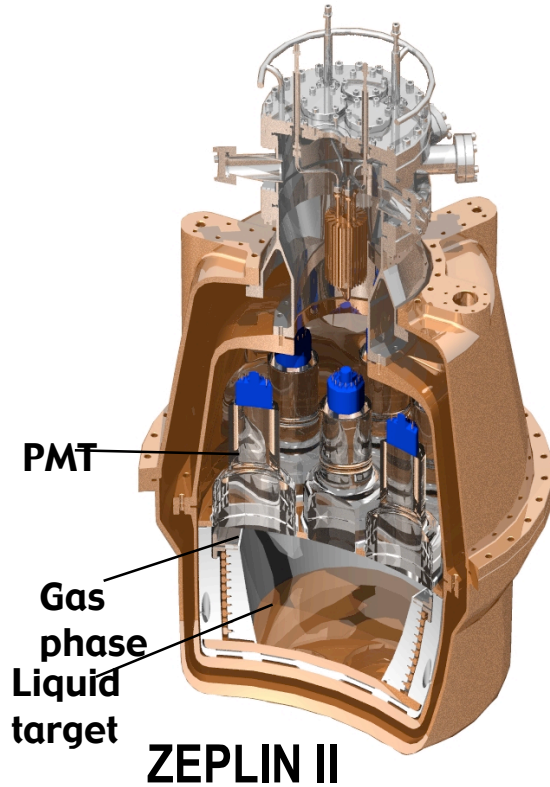
## Photons and alphas



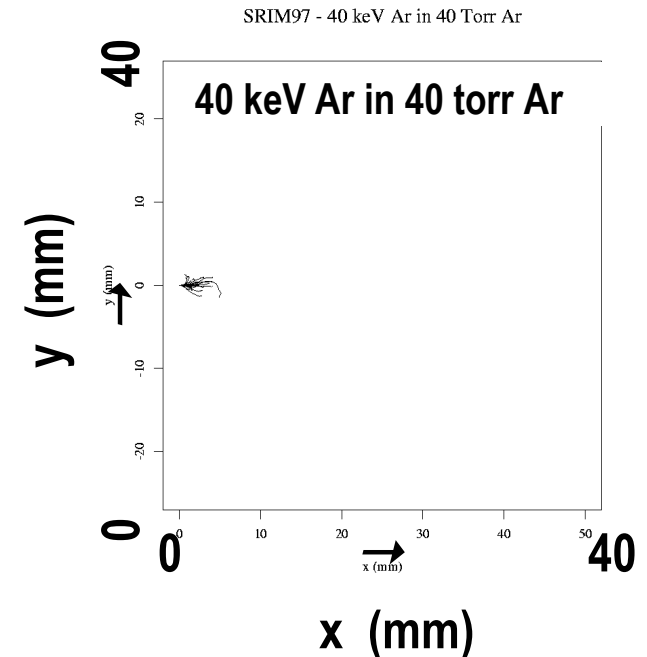
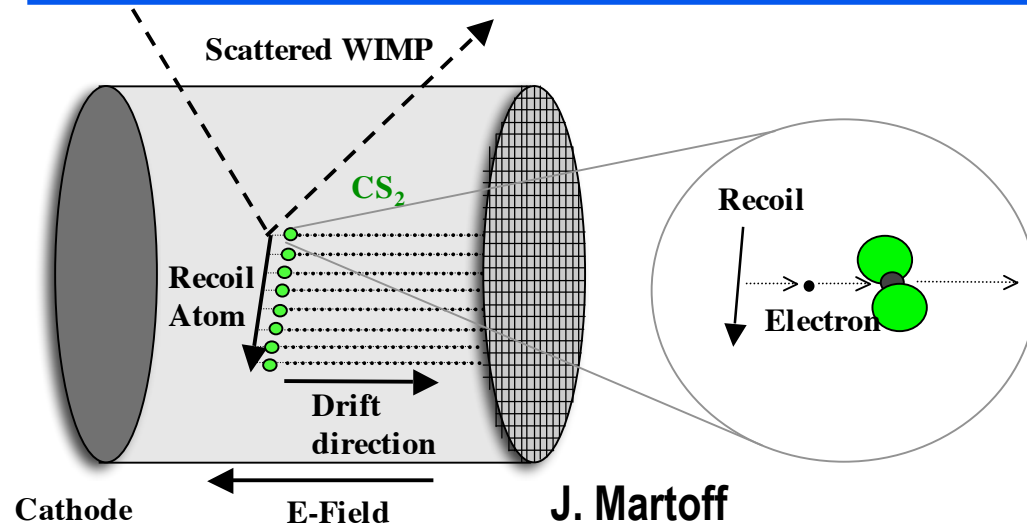
Must increase light collection 15x to get 15 keV threshold for WIMPs

- ♦ PMTs at bottom of detector
- ♦ CsI photocathode
- ♦ Alternate light readout? (LAAPDs?)

## 'XENON' Collaboration (Columbia et al)

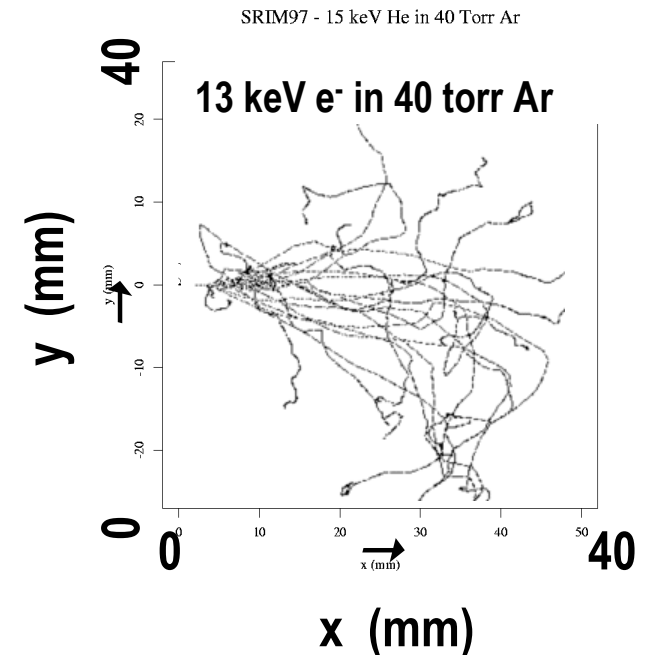
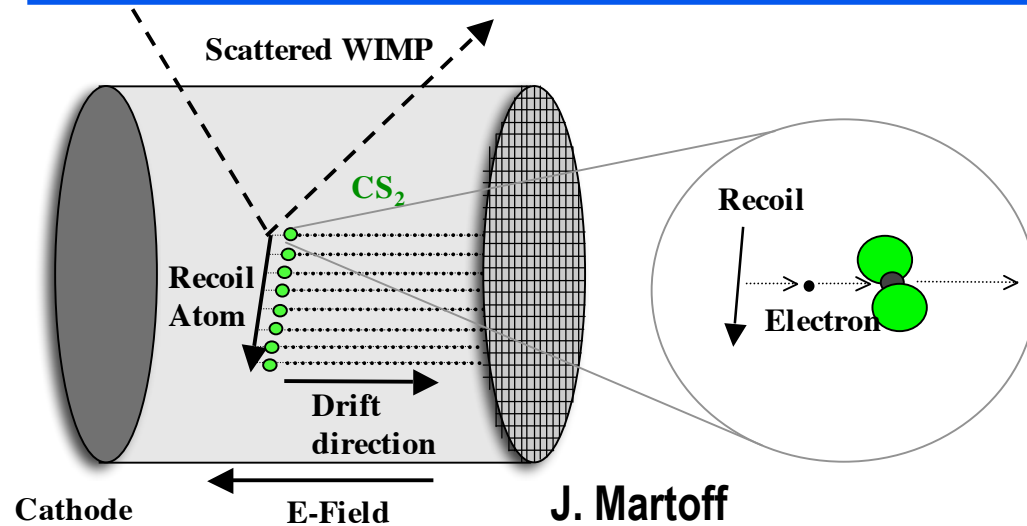


# Directional: DRIFT

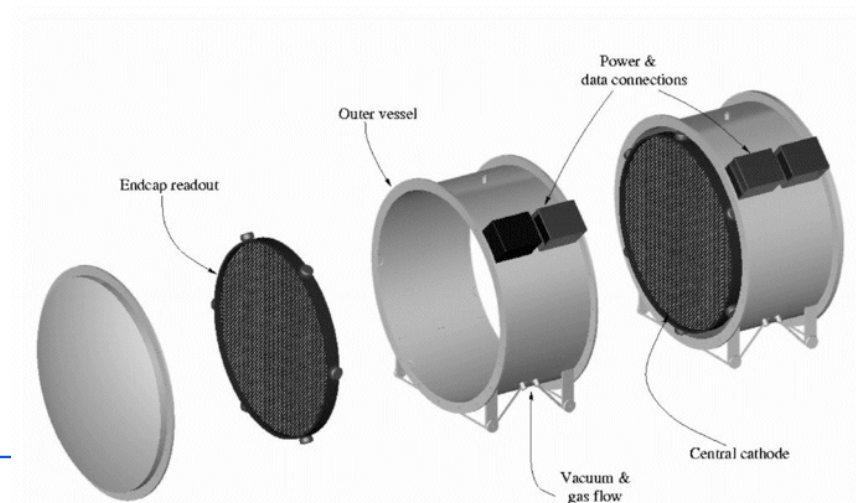


- Sensitive to direction of recoiling nucleus
  - ♦ Diurnal modulation signal – galactic origin of signal
- Drift negative ions in TPC
  - ♦ No magnet
  - ♦ Reduced diffusion
- Electron recoils rejected via  $dE/dx$
- DRIFT I
  - ♦ Cubic meter in Boulby since 2001
  - ♦ Engineering runs completed
- DRIFT II extension to 10 kg module proposed

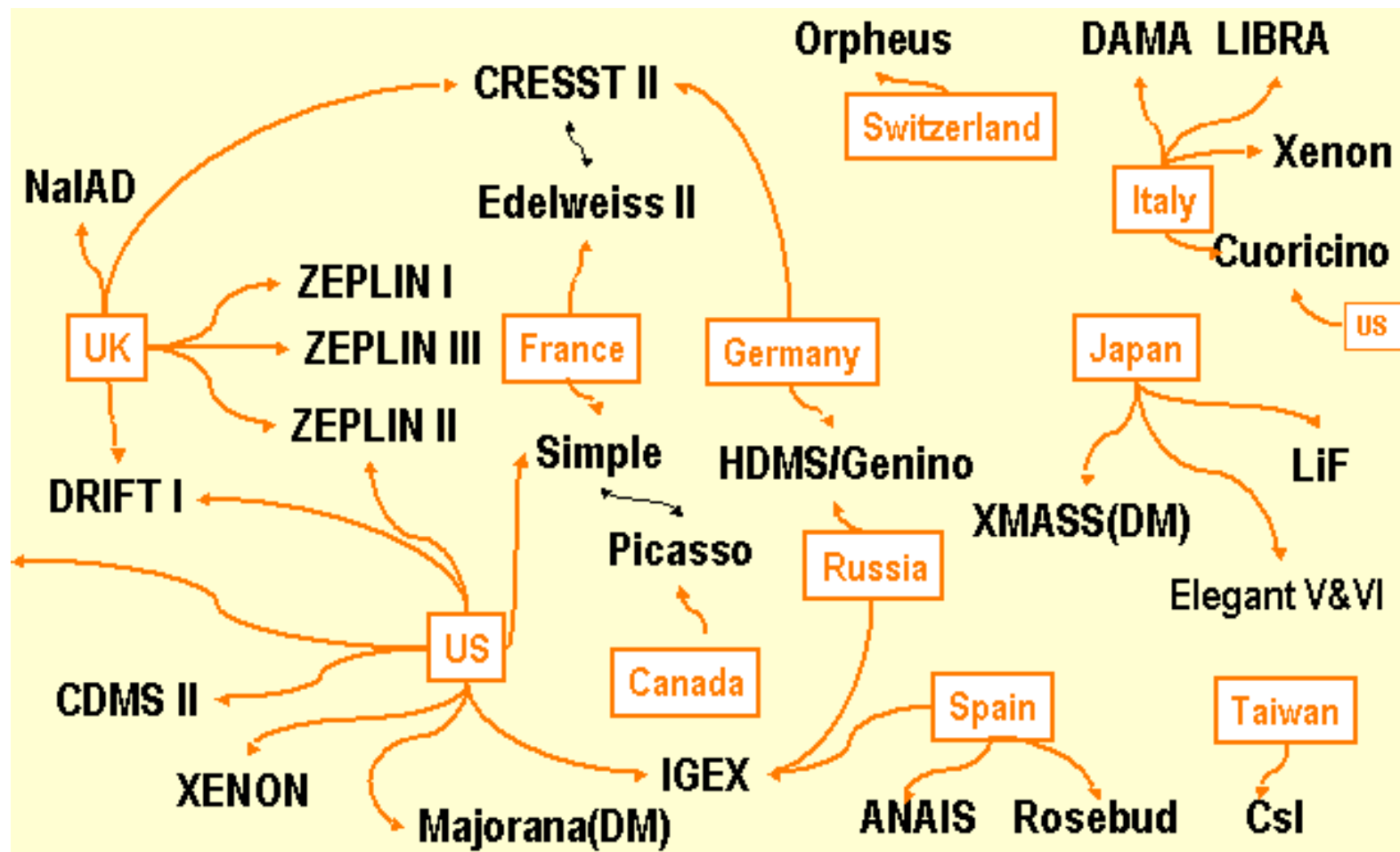
# Directional: DRIFT



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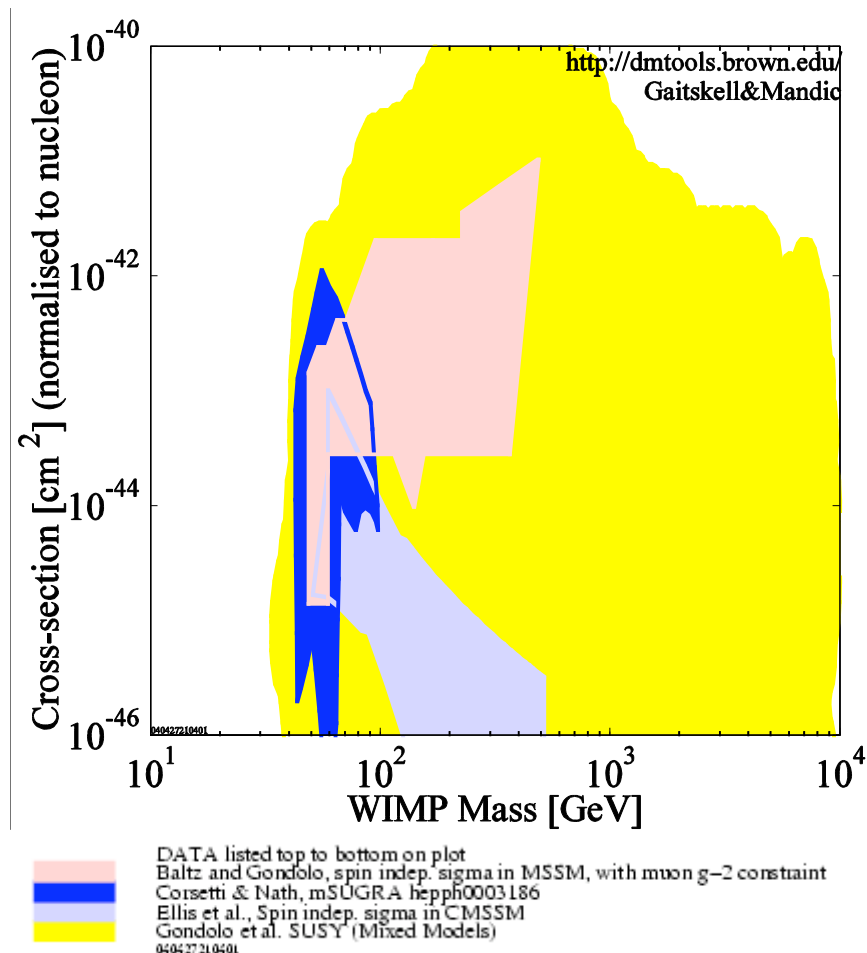
# World View on WIMPs



Courtesy of R. Gaitskill

# Dark Matter Summary and Projections

- Dark matter
  - ♦ Basic component of Universe
  - ♦ Withstood major revisions to advances in cosmology
  - ♦ New particle physics → Complementarity to accelerator experiments - LHC in 2007
  - ♦ Detection of WIMP annihilation products
- Several direct-search technologies on line and leading to steady progress
  - ♦ CDMS, Edelweiss, Zeplin, Cresst
  - ♦ Active R&D efforts
- Expansion to ton-scale
  - ♦ ZepMAX, Cryoarray, XENON...



# Dark Matter Summary and Projections

- Dark matter

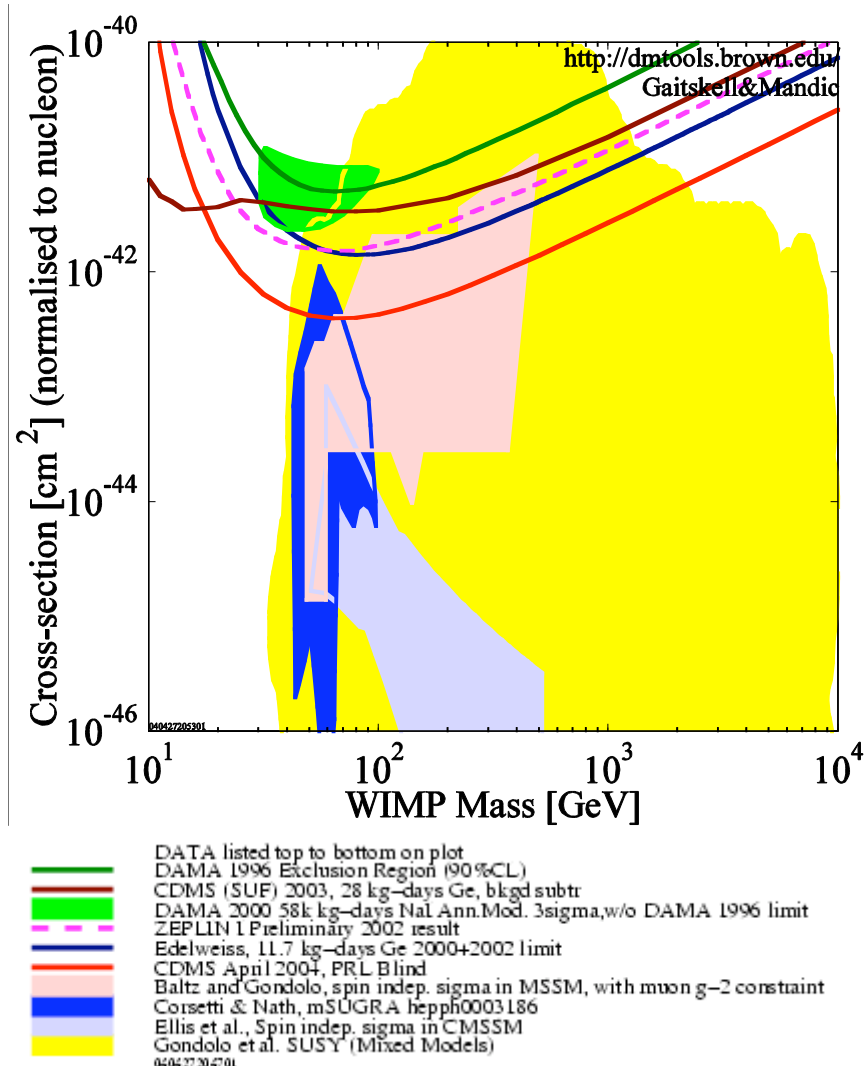
- ◆ Basic component of Universe
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- ◆ Active R&D efforts

- Expansion to ton-scale

- ◆ ZepMAX, Cryoarray, XENON...



# Dark Matter Summary and Projections

- **Dark matter**

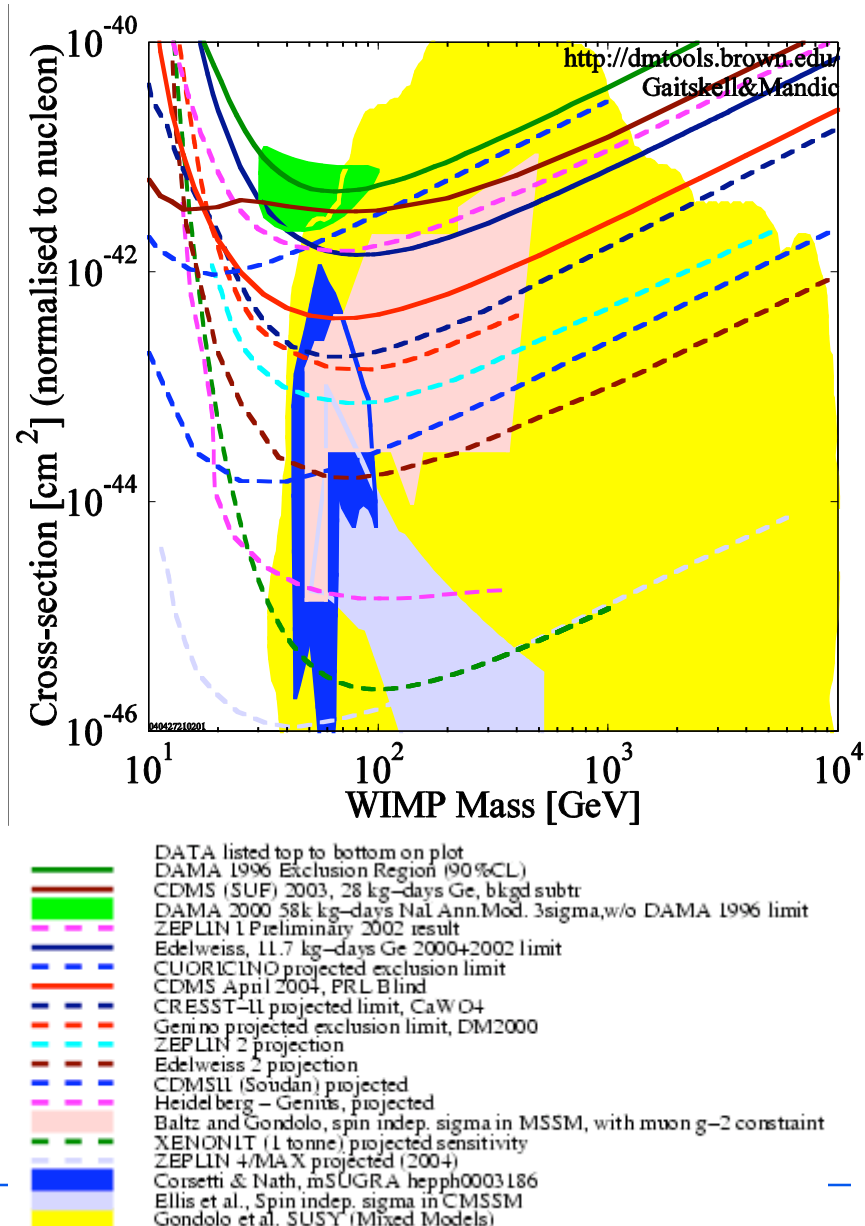
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- **Several direct-search technologies on line and leading to steady progress**

- ◆ CDMS, Edelweiss, Zeplin, Cresst
- ◆ Active R&D efforts

- **Expansion to ton-scale**

- ◆ ZepMAX, Cryoarray, XENON...



# Dusel & Dark Matter: some perspectives

---

- **Suppression of muon-induced neutron background is essential**
    - ◆ Simply put, deeper is better
    - ◆ A shallower site (eg, <6000mwe for a ton-scale experiment) would require some active component for shielding/vetoing neutrons
      - Could raise questions of efficiency and systematics
  - **Internal backgrounds — to take advantage of the neutron suppression afforded by these depths requires:**
    - ◆ Scaling up the detector mass
    - ◆ Detector R&D - Various approaches from (cryogenic, xenon, etc) must deliver on the ongoing R&D
    - ◆ Advance the techniques for screening and suppressing internal backgrounds (separate working group on LBCFs - H.Miley & P. Cushman)
      - New ideas recently having an impact - eg, surface chemistry techniques, gas detectors with no passive material
      - These would naturally be at home at a Dusel
-

# Open Questions

---

- Much work was done on question of depth at and since the Lead workshop, NESS, NFAC...etc -- working group should build on this
    - ◆ Progress with neutron-production Monte Carlo's, eg, Fluka, are coming into wider use -- use these to update our estimates
    - ◆ Consider the role and reach of active vetos - at what scale-vs-depth are they needed?
      - Experiment specific or cavern-wide?
      - Contingencies for beyond ton-scale?
  - Space needs
    - ◆ Modest in most cases: few thousand sq ft, but high overhead space to accommodate shielding, cranes, etc. (~25-30')
    - ◆ Large gas TPC (eg, Drift) could require large hall - depending on the required reach (what's the WIMP-nucleon cross section???)
  - Specialized needs/facilities (a partial list to consider)
    - ◆ Radon suppression
    - ◆ Clean rooms
    - ◆ Fabrication/shops
    - ◆ Low-noise and uninterruptable power
    - ◆ Cryogen supplies/safety
-

# Harder Open Questions

---

- What do envision for the longer term at DUSEL, ie, beyond the round of experiments we currently envision?
  - ◆ If Dark Matter not found -- too many unknowns to make robust predictions -- in time we will have new information from indirect searches, LHC, etc. If we don't see a signal at the ton-scale (or even 10 tons) will there still be motivation to go beyond?
    - Without a sign, SUSY DM could be reduced to a fine-tuned 'unnatural' answer
  - ◆ Dark Matter found -- confirm galactic origin, eg, large scale Drift or alternative directional detectors → WIMP astronomy, learning about the galaxy → broader implications
- Beyond WIMPs and the 20+year plan?
  - ◆ What brought us together is the interest in fundamental physics and the willingness (or penchant!?) to build innovative instruments sensitive to subtle signals
  - ◆ How can we build on this to experimentally access new questions?
    - Dark energy - miniscule pressure
    - Neutrinos - coherent scattering (solar, SN); relic neutrino background
    - Gravity experiments - low seismic noise environment
    - ???

---

Keywords for the lab's future: flexibility, expansion, adaptable - but...

# One example...

- Cabrera, Krauss, & Wilczek - PRL 55, 1 July 1985

- ◆ Bolometric Detection of Neutrinos (10 tons, coherent scattering)

## Bolometric Detection of Neutrinos

BILL CABRERA, LAWRENCE M. KRAUSS, and FRANK WILCZEK

*Department of Physics, Stanford University, Stanford, California 94305  
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138  
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106  
(Received 14 December 1984)*

elastic scattering off electrons in crystalline silicon at 1–10 mK results in measurable temperature changes in macroscopic amounts of material, even for low-energy ( $< 0.42$  MeV)  $\mu\mu$   $\nu$ 's from the sun. We propose new detectors for bolometric measurement of low-energy  $\nu$  interactions, including coherent nuclear elastic scattering. A new and more sensitive search for oscillations of reactor antineutrinos is practical ( $\sim 100$  kg of Si), and work for the groundwork for a more ambitious measurement of the spectrum of  $\mu\mu$   $\nu$ 's, and  $\nu$  solar  $\nu$ 's, and supernovae signals where in our galaxy ( $\sim 10$  tons of Si).

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The problems associated with the detection of low-energy neutrinos are both well known and numerous. For example, in spite of its clear scientific importance and after two decades of heroic efforts, the  $\nu$  spectrum from the sun has still not been measured. Traditionally, low-energy neutrino detection has involved measurement of induced nuclear transmutations.<sup>1–3</sup> In this Letter we explore a new, bolometric method. This method can provide a new practical detector for making more sensitive measurements of reactor  $\nu$ 's, and our lead to a detector for measuring the spectrum of neutrinos emitted from the solar core.

The differential cross section for a  $\nu$  or  $\bar{\nu}$  with energy  $E$  to scatter elastically off an electron with recoil energy  $T$  is given by<sup>4</sup>

$$d\sigma/dT = (G_F^2 m_e / 2\pi) [(C_V + C_A)^2 + (C_V - C_A)^2] (1 - T/E)^2 - (C_V^2 - C_A^2) m_e T/E^2, \quad (1)$$

where, for  $\nu_e$  ( $\bar{\nu}_e$ ),  $C_V = 2 \sin^2 \theta + \frac{1}{2}$  and  $C_A = \frac{1}{2}$  ( $-\frac{1}{2}$ ), and for  $\nu_\mu$  ( $\bar{\nu}_\mu$ ),  $C_V = 2 \sin^2 \theta - \frac{1}{2}$  and  $C_A = \frac{1}{2}$  ( $-\frac{1}{2}$ ). The difference between  $\nu_e$  and  $\nu_\mu$  scattering arises because charged and neutral currents contribute to the former, but only neutral currents to the latter. The total cross section is then given by integration of Eq. (1) from  $T=0$  to  $T_{\max} = 2E^2/(2E+m)$ .

In order to determine rates for solar- $\nu$  interactions, we calculate cross sections for production of electrons in a given energy range weighted over solar- $\nu$  spectra. Rates are then calculated with use of the integrated fluxes of Bahcall,<sup>5</sup> and with use of the fact that there are fourteen electrons per Si atom (with  $\sin^2 \theta_w \sim 0.23$ ). Our results are presented in Table I and Fig. 1.

As seen from Table I, a detector of recoil electrons is most sensitive to the  $\mu\mu$  and  $\nu$ Be solar  $\nu$ 's. The  $\mu\mu$  neutrinos produce recoil electrons with a frequency of  $\sim 1 \text{ cm}^{-2} \text{ d}^{-1}$  for silicon, about 360 times the total rate currently achieved with the  $^{37}\text{Cl}$  detector.<sup>1</sup> As shown in Fig. 1, they produce recoil energies below 280 keV. The  $\nu$ Be neutrinos interact about half as often, and produce recoil electrons with energies up to 660 keV. As a result of the relatively flat differential cross section [Eq. (1)] and the monochromatic nature of the electron-capture  $\nu$ Be  $\nu$ 's, their recoil electron spectrum has a sharp cutoff at its upper energy, making signal detection easier. In fact, the width of the  $\nu$ Be  $\nu$  energy ( $\sim 1$  keV) is determined by the solar-core temperature ( $\sim 10^8$  K). Measurement of the resultant rounding of the recoil electron energy cutoff

could directly determine the solar-core temperature. The electron events produced by  $\nu$ Be  $\nu$ 's have a higher weighted average cross section with energies up to 13 MeV, but do not appear in Fig. 1 because of the substantially reduced flux.

However, coherent scattering off nuclei for these highest energy  $\nu$ 's produces energy transfers up to about 10 keV with large rates, resulting in a peak below the significant energy range for the  $\mu\mu$  electrons (see Fig. 1). The coherent cross section for vector neutral-current scattering off nuclei is given by

$$\sigma_{\text{coh}} = G_F^2 L^2 (Z - 4 \sin^2 \theta_w - N)^2 / 4\pi$$

(independent of  $\nu$  type), where  $N$  is the number of neutrons in nucleus, and  $Z$  is the nuclear charge.<sup>6</sup>

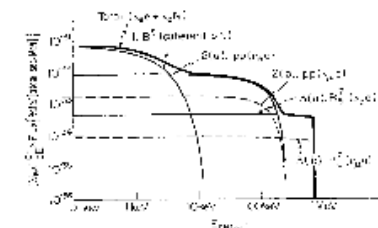


FIG. 1. Event rate vs recoil energy for various sources.

# Challenge to our working group

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- While the 10-20 year plan is 'clear' (and exciting!), we need to try to improve on the long-term strategy of: **"If you build it, they will come..."**

